PB-222 052

USE OF DOMESTIC WASTE GLASS FOR URBAN PAVING

MISSOURI UNIVERSITY

PREPARED FOR
ENVIRONMENTAL PROTECTION AGENCY

JULY 1973

Distributed By:

NTIS
National Technical Information Service
U. S. DEPARTMENT OF COMMERCE

BIBLIOGRAPHIC DATA SHEET	1. Report No. EPA-670/2-73-038	2.	3. Recipient's Accession No. PB-222 052
4. Title and Subtitle USE OF DOMESTIC WASTE GLASS FOR URBAN PAVING			5. Report Date 1973-issuing date 6.
7. Author(s) W. R. Malisch, D. E. Day, and B. G. Wixson			8. Performing Organization Rept. No.
9. Performing Organization Name and Address Department of Civil Engineering University of Missouri Rolla, Missouri 65401			10. Project/Task/Work Unit No. 11. Contract/Grant No. EP-00329
12. Sponsoring Organization Name and Address U.S. Environmental Protection Agency National Environmental Research Center Office and Research & Development Cincinnati, Ohio 45268			13. Type of Report & Period Covered Final 14.

15. Supplementary Notes

16. Abstracts This report summarizes research on the use of waste glass as an aggregate in asphaltic paving mixtures. Reusing waste glass in this manner would provide an outlet for large quantities of the glass and would permit recycling in urban areas where large accumulations of glass are found. Field tests as well as observatations of pavement performance have indicated that field installations of asphaltic paving mixtures containing glass have generally maintained adequate skid resistance and performed acceptably from a structural standpoint. The economic feasibility of using waste glass as an aggregate in asphaltic concrete depends primarily on developing resource recovery systems that can separate glass along with other recyclable components and generate enough revenues from their sale, plus disposal and processing fees, to produce an acceptable return on equity.

17. Key Words and Document Analysis. 17a. Descriptors

Skid resistance, * Urban areas, * Glass, * Asphalts, Bituminous concretes, Aggregates, Pavements, Economic analysis, Revenue, Surface properties and textures, Sieve analysis

17b. Identifiers/Open-Ended Terms

Recycling; * Solid waste management; * Resource recovery; Marshall design; Hydrated lime; Glass-asphalt; Cullet; Rolla, Missouri; Fullerton, California; Bramalea, Ontario; Brockway, Pennsylvania; Burnaby, British Columbia; Omaha, Nebraska; Scarborough, Ontario

17c. COSATI Field/Group 11B; 13B

18. Availability Statement Release to public	19. Security Class (This Report) UNCLASSIFIED	21. No. of Pages 106
	20. Security Class (This Page) UNCLASSIFIED	22. Price

FORM NTIS-35 (REV. 3-72) THIS FORM MAY BE REPRODUCED USCOMM-DC 14952-P72

EPA-670/2-73-038
July 1973

PB 222 052

USE OF DOMESTIC WASTE GLASS FOR URBAN PAVING

By

W. R. Malisch, D. E. Day, and B. G. Wixson
Department of Civil Engineering
University of Missouri
Rolla, Missouri 65401

Grant No. EP-00329
Program Element No. 1D2064

Project Officer

Kent S. Kisenbauer
Solid Waste Research Laboratory
National Environmental Research Center
Cincinnati, Ohio 45268

Prepared for
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
WASHINGTON, D.C. 20460

REVIEW NOTICE

The Solid Waste Research Laboratory of the National Environmental Research Center - Cincinnati, U.S. Environmental Protection Agency, has reviewed this report and approved its publication. Approval does not signify that the contents necessarily reflect the views and policies of this laboratory or of the U.S. Environmental Protection Agency, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

The text of this report is reproduced by the National Environmental Research Center - Cincinnati in the form received from the Grantee; new preliminary pages have been supplied.

FOREWORD

Man and his environment must be protected from the adverse effects of pesticides, radiation, noise and other forms of pollution, and the unwise management of solid waste. Efforts to protect the environment require a focus that recognizes the interplay between the components of our physical environment--air, water, and land. The National Environmental Research Centers provide this multidisciplinary focus through programs engaged in

- studies on the effects of environmental contaminants on man and the biosphere, and
- a search for ways to prevent contamination and to recycle valuable resources.

In an attempt to solve the problem of solid waste management, this study, published by the National Environmental Research Center - Cincinnati, examines research on the use of waste glass as an aggregate in asphalt paving mixtures. The potential for using waste glass in asphaltic pavements is demonstrated in this report.

A. W. Breidenbach, Ph.D.
Director
National Environmental
Research Center - Cincinnati

ABSTRACT

Recycling has been suggested as a solution to the problem of disposing of the increasing quantities of solid wastes generated in the United States each year. This report summarizes research on the use of waste glass as an aggregate in asphaltic paving mixtures. Re-using waste glass in this manner would provide an outlet for large quantities of the glass and would permit recycling in urban areas where large accumulations of glass are found.

Initial laboratory studies showed that asphaltic mixtures satisfying Marshall design requirements could be designed using all-glass aggregates and that adequate water-resistance could be achieved by adding hydrated lime to the aggregates. Conventional aggregate gradations for dense-graded mixtures could be used in the mixture and the presence of flat and elongated particles in the coarse fraction was found to cause little change in the Marshall properties of glass-asphalt mixtures.

Field installations of asphaltic paving mixtures containing glass have been placed in several states and in Canada and field tests as well as observations of the pavement performance have indicated that these installations have generally maintained adequate skid resistance and performed acceptably from a structural standpoint. Surface deterioration or raveling, however, has occurred on some of the pavements and further study of the cause of this raveling is needed.

Based upon the results of a laboratory wear test developed in this investigation, paving mixtures containing glass aggregates are more abrasive than mixtures containing some conventional aggregates. However, the data obtained in the laboratory wear test are not in agreement with the findings reported in a British study of tire wear resulting from surfaces with varying roughness and micro-texture. Further road testing to compare tire wear produced by pavements containing glass and conventional aggregates is recommended.

The economic feasibility of using waste glass as an aggregate in asphaltic concrete is dependent primarily upon the development of resource recovery systems which can separate glass along with other recyclable components and generate enough revenues from their sale plus disposal and processing fees to produce an acceptable return on equity. At the present time it appears that such a system can be economically viable in a limited number of municipalities. The maximum contribution to reclaimed product revenues would result if the glass were color sorted and marketed as cullet. However, if an acceptable level of color sorting is not possible or if there are no local markets for the cullet, use of the waste glass as aggregate should be considered.

CONTENTS

	Page
CONCLUSIONS	1
RECOMMENDATIONS	3
INTRODUCTION	5
INITIAL DESIGN STUDIES	12
WATER RESISTANCE STUDIES	21
EFFECTS OF PARTICLE SHAPE, ANGULARITY AND GRADATION UPON MIXTURE PROPERTIES	25
FIELD EXPERIENCE WITH GLASS-ASPHALT PAVEMENTS	38
EVALUATION OF GLASS-ASPHALT PAVEMENT PERFORMANCE	68
EFFECTS OF GLASS AGGREGATES UPON ABRASIVENESS OF ASPHALTIC MIXTURES	76
ECONOMIC ANALYSIS	83
ACKNOWLEDGMENTS	90
REFERENCES	91
LIST OF PUBLICATIONS	94

FIGURES

Figure		Page
1	Marshall Test Properties from Initial Mix Design (Gradation No. 1)	15
2	Marshall Test Properties from Initial Mix Design	17
3	Effects of Anti-Stripping Agents on Retained Strength	24
4	Bulk Density Resulting from Variable Grading Ratios for Glass Aggregates	28
5	Void Contents Resulting from Variable Grading Ratios for Glass Aggregates	29
6	Marshall Test Properties of Glasphalt with Maximum Bulk Density Gradation (n = .375)	31
7	Marshall Test Properties of Glasphalt with Modified Maximum Bulk Density Gradation	32
8	Rolla Glasphalt Road Immediately after Placement	41
9	Variations in Skid Resistance with Time for Rolla Glasphalt Road	44
10	Rolla Glasphalt Road after Two Years of Service	45
11	Surface Texture of Rolla Glasphalt after Two Years of Service	45
12	Alligator Cracking in Localized Area of Rolla Glasphalt Road	46
13	Fullerton Glasphalt Road Immediately after Placing	50
14	Surface Texture of Fullerton Glasphalt Road after One Year of Service	50
15	Surface Texture of Bramalea Glasphalt Road after 15 Months of Service	54
16	Depression in Bramalea Glasphalt Road Caused by Concentrated Load	54

FIGURES
(continued)

Figure		Page
17	Raveling of Scarborough Glasphalt Street after One Year of Service	57
18	Glasphalt Parking Lot in Brockway after One Year of Service	59
19	Raveling of Glasphalt Road in Burnaby after One Winter	62
20	Surface Pitting of Burnaby Glasphalt Road Caused by Loss of Glass Particles	62
21	Pot-Hole in Burnaby Glasphalt Road after Nine Months of Service	63
22	Variations in Skid Resistance with Time for Asphaltic Concrete Patches Containing Different Aggregates	71
23	Schematic Diagram of Laboratory Wheel Abrasion Testing Apparatus	77

TABLES

Table		Page
1	Glasphalt Pavements Placed in the United States and Canada	9
2	Shape Characteristics of Crushed Glass Used in Initial Design Studies	12
3	Properties of Asphalt Used in Initial Design Studies	13
4	Gradation of Crushed Glass Used in Initial Design Studies	14
5	Marshall Method Data for Initial Design Studies	16
6	Marshall Design Criteria Recommended by the Asphalt Institute for Medium Traffic	16
7	Results of Sieve Analyses of Extracted Aggregates	18
8	Immersion-Compression Test Results for Commercial Anti-Stripping Additives	22
9	Immersion-Compression Test Results for Hydrated Lime and Limestone Dust Additives	23
10	Flat and Elongated Particle Count for Crushed Bottle Glass	25
11	Flat and Elongated Particle Count for Drain Cullet and Crushed Tempered Glass	26
12	Properties of Asphalt	26
13	Modifications in Gradation Used for Marshall Specimens Containing Crushed Bottle Glass	35
14	Results of Marshall Tests on Specimens with Modified Gradation	35
15	Composition of Glass-Asphalt Mixtures Using Glass Aggregates of Varying Shape and Angularity	36
16	Marshall Properties of Glass-Asphalt Mixtures Containing Glass Aggregates of Varying Shape and Angularity	37

TABLES
(continued)

Table		Page
17	Aggregate Gradation for Design Studies of Rolla Glasphalt	39
18	Laboratory Marshall Mix Design Results for Rolla Glasphalt	39
19	Coarse Mixture Gradation Based on Hot Bin Analysis for Rolla Glasphalt	40
20	Fine Mixture Gradation Based on Hot Bin Analysis for Rolla Glasphalt	40
21	Marshall Properties of Field Samples for Rolla Glasphalt	41
22	Results of Density Tests for Rolla Glasphalt	42
23	Results of Sieve Analyses for Rolla Glasphalt Samples	42
24	Aggregate Gradation for Design Studies of Fullerton Glasphalt	47
25	Marshall Mix Design Results for Fullerton Glasphalt	47
26	Gradation Based on Hot Bin Analysis for Fullerton Glasphalt	48
27	Marshall Properties for Plant Sample of Fullerton Glasphalt	48
28	Results of Density Tests for Fullerton Glasphalt	49
29	Results of Sieve Analyses of Fullerton Glasphalt Samples	49
30	Aggregate Gradation for Bramalea Glasphalt	51
31	Marshall Properties of Bramalea Design Mix	52
32	Marshall Test Results for Bramalea Field Samples	52
33	Extraction Results for Bramalea Field Samples	53

TABLES
(continued)

Table		Page
34	Results of Laboratory Tests on Bramalea Cores	53
35	Aggregate Gradation for Scarborough Glasphalt	55
36	Marshall Test Results for Scarborough Field Samples	56
37	Extraction Results from Scarborough Field Samples	56
38	Aggregate Gradation for Design Studies of Brockway Glasphalt	58
39	Marshall Mix Design Results for Brockway Glasphalt	58
40	Gradation Based on Cold Feed for Brockway Glasphalt	58
41	Aggregate Gradation for Burnaby Glasphalt	60
42	Marshall Properties of Burnaby Design Mix	61
43	Results of Burnaby Skid Tests	64
44	Aggregate Gradation for Design Studies of Omaha Glasphalt	66
45	Marshall Mix Design Results for Omaha Glasphalt	67
46	Gradation of Omaha Glasphalt as Produced	67
47	Marshall Properties of Plant Samples for Omaha Glasphalt	67
48	Recommended Minimum Skid Resistance Requirements	68
49	Gradation of Aggregates Used in Patches for Skid Resistance Tests	70
50	Marshall Properties of Laboratory Specimens for Skid Resistance Patches	70
51	Marshall Properties of Laboratory Compacted Field Samples from Skid Resistance Patches	72

TABLES
(continued)

Table		Page
52	Skid Resistance of Field Patches After 23 Months of Service	72
53	Skid Resistance of Field Patches After 19 Months of Service	73
54	Angularity of Fine Aggregates Used in Wear Studies	78
55	Wheel Weight Losses on Asphaltic Mixtures with Various Coarse Aggregrates	80
56	Wheel Weight Losses on Asphaltic Mixtures with Various Fine Aggregrates	80
57	Wheel Weight Losses on Field Patches with Various Aggregates	81
58	Wheel Weight Losses for Surfaces with Varying Coefficients of Friction	82
59	Assumed Annual Revenues from Resource Recovery System	88
60	Assumed Return on Equity from Resource Recovery System	89

CONCLUSIONS

Asphaltic mixtures satisfying Marshall design criteria recommended by the Asphalt Institute can be designed using penetration grade asphalts and aggregates composed entirely of crushed glass or mixtures of glass and conventional aggregates. Optimum asphalt contents are in the same range (4 to 7 percent) as those required for conventional aggregates.

Water resistance of glass-asphalt mixtures as measured by laboratory immersion-compression tests is adequate if hydrated lime is added to the mixture in an amount equal to at least one percent by weight of the aggregate. Commercial anti-stripping agents are less effective and the addition of limestone dust does not improve water resistance.

Higher densities for asphaltic mixtures containing glass aggregates can be obtained by altering the grading ratio normally used to produce maximum densities with conventional aggregates. However, this results in air voids and voids in the mineral aggregate which are below minimum acceptable values. Thus, higher stabilities which accompany increased density are obtained at the expense of maintaining a minimum void content to reduce flushing of asphalt to the surface.

Substitution of angular but nearly equidimensional coarse glass particles for flat and/or elongated particles obtained by crushing container glass does not appreciably affect Marshall properties of asphaltic concrete at a constant asphalt content.

Standard batch plants can be used for mixing asphaltic mixtures containing glass aggregates, but a mechanical dust feeder would be desirable since hydrated lime is necessary to control stripping and manual addition of the lime may result in delays or inconvenience in the mixing process.

Asphaltic mixtures containing glass aggregates can be placed and compacted using conventional equipment. These mixtures may be difficult to compact due to horizontal mix displacement (crawl) during rolling, and this may necessitate a delay before breakdown rolling. However, breakdown rolling should commence as soon as the mat can support the roller without lateral deformation.

Aggregate degradation as a result of compaction and subsequent traffic over pavements containing glass aggregates is relatively small for roads carrying light to medium traffic except when studded tires are used.

The skid resistance of pavements containing glass aggregates is adequate for streets carrying up to 6000 vehicles per day with speeds up to 30 mph and in service for up to two

years. The substitution of coarse container glass particles for conventional coarse aggregate may result in lower skid resistance but the replacement of river sand with crushed glass fines has no effect upon skid resistance.

Properly designed and constructed asphaltic pavements containing glass aggregates can be expected to perform well structurally, with little rutting, cracking, or potholing occurring. Excessive raveling, however, may develop in pavements exposed to studded tire traffic and raveling to a lesser degree may occur due to normal traffic.

Based upon the results of a laboratory wear test developed in this investigation, paving mixtures containing glass aggregates are more abrasive than mixtures containing some conventional aggregates. However, the data obtained in the laboratory wear test are not in agreement with the findings reported in a British study of tire wear resulting from surfaces with varying roughness and micro-texture.

The economic feasibility of using waste glass as an aggregate in asphaltic concrete is dependent primarily upon the development of resource recovery systems which can separate glass along with other recyclable components and generate enough revenues from their sale plus disposal and processing fees to produce an acceptable return on equity. At the present time, it appears that such a system can be economically viable in a limited number of municipalities. The maximum contribution to reclaimed product revenues would result if the glass were color sorted and marketed as cullet. However, if an acceptable level of color sorting is not possible or if there are no local markets for the cullet, use of the waste glass as aggregate is preferable to disposing of it in a sanitary landfill. This usage would generate some revenues without incurring additional disposal costs.

RECOMMENDATIONS

Design of asphaltic paving mixtures containing glass aggregates should be carried out in accordance with standard design methods such as the Marshall test procedures outlined in Mix Design Methods for Asphalt Concrete, published by The Asphalt Institute. It is recommended that local gradation requirements commonly specified for dense-graded asphaltic concrete be used for mixtures containing glass aggregates and that the aggregate contain at least one percent hydrated lime by weight.

Conventional batch plants and paving and compaction equipment can be used in paving with glasphalt but it is recommended that a mechanical dust feeder be used at the batch plant for adding hydrated lime to the mixture. The hydrated lime may be added manually at the pugmill but this may result in delays or inconvenience in the mixing process.

Standard construction methods should be used in placing glasphalt pavements, with care being taken to insure adequate field density. If horizontal mix displacement occurs during rolling, a lighter roller, a delay in rolling to permit cooling of the mix, or a combination of the two should be employed to compact the pavement.

Although adequate Marshall properties have been obtained for asphaltic mixtures containing glass aggregates, the raveling of some glasphalt pavements which has occurred under service conditions points to the need for further observation of the abrasion resistance of glasphalt pavements. The interaction of factors such as the amount of studded tire traffic, traffic volume and pavement density which affect the raveling characteristics of pavements containing glass aggregates should be studied in more detail. If studded tires are the primary cause of excessive raveling it will be necessary to restrict the use of glasphalt to binder or base course applications in areas where studded tires are in use. If excessive raveling is caused by higher traffic volumes, regardless of whether or not studded tires are in use, it may be necessary to restrict the maximum size of glass particles used in the pavement or to confine the use of glasphalt mixtures to binder or base courses.

Since results of laboratory wear tests indicate that the use of glass aggregates may produce a more abrasive pavement surface, a comparison of the tire wear resulting from glass aggregates and conventional aggregates is needed. Road tests are preferred to laboratory tests on a stationary specimen, due to the difficulties in interpreting results obtained when abrasion of the test surface is caused by the test wheel.

While the skid resistance of pavements containing glass aggregates has proved to be adequate, tests have shown that replacement of crushed stone coarse aggregate with glass particles in mixtures of similar gradation and asphalt content reduces skid resistance. Thus it is recommended that for surface courses, the use of coarse glass aggregates should be restricted to roads carrying low-speed traffic (30 mph or less).

The experimental field installations of glasphalt placed to this date have utilized clean glass containers which were crushed to obtain the desired gradation. Placing and performance characteristics of the pavements were of primary interest and crushing costs for the glass were not a major concern. However, unit crushing costs are likely to be high when relatively small amounts of glass are crushed because of the time consumed in adjusting crusher settings for feeding the containers, making necessary modifications to produce the desired gradation and cleaning glass out of the crusher upon completion of the crushing operation. For this reason, small volumes of crushed glass prepared in this manner cannot be processed at as low a cost as conventional aggregate, and use in glasphalt is not recommended as an economical means for reusing glass under these conditions. Resource recovery systems which are currently being developed incorporate crushing at several stages in the process, though, so that the glass fraction produced would be in a usable form without further crushing. It is recommended that this glass fraction be considered for use as aggregate since such a usage has been shown to be technically feasible.

INTRODUCTION

Need for the Study

The increasing quantity and changing character of solid wastes generated in the United States each year have resulted in an urgent need to develop improved means for processing and disposing of these wastes. Recycling and re-use of materials have been suggested as a solution to this problem.

The rationale for recycling generally includes reduction of the volume of the waste stream destined for final disposal as well as conservation of resources. Factors of importance when considering a recycling program for any waste component are, therefore, the volume or size of the fraction of the waste stream constituted by a particular type of waste, and the nation's source of raw materials from which the item or group of items were made. Obstacles to recycling are the heterogenity of wastes, high transportation costs if reclaimed materials cannot be used in the area where they are generated, lack of stable markets and prices for salvageable materials, and absence of a suitable technology for separating and treating mixed refuse.[1] All these factors have been considered in the development of a new means for recycling one of the waste components -- glass.

Approximately 250 million tons of household, commercial, and municipal wastes are generated in the United States each year,[2] and studies of refuse composition indicate that glass comprises some 6 to 11 percent by weight of this material[3-5] or at least 15 million tons annually.[6] While this does not represent a major portion of the total waste stream, recycling a significant amount of glass would decrease the volume of material destined for ultimate disposal. However, due to the abundance and low cost of the principal raw materials used for glass manufacture, conservation of resources is not a major incentive for recycling at the present time.

Waste glass (cullet) has historically been used in the manufacture of new glass containers.[7] This represents the highest value of re-use since cullet of suitable quality has a raw material replacement value of 10 to 20 dollars per ton. However, glass used in this manner must be essentially free of non-glass components and color-sorted. Even if suitable technology is developed for separating municipal wastes, the economic benefits from such a separation will depend upon the availability of markets, with an important consideration being the transportation costs involved.

The research described in this final report deals with the use of waste glass as an aggregate in asphaltic mixtures used for urban paving and street maintenance operations. Many of the problems in recycling waste glass to glass furnaces can be avoided by using the glass as an aggregate. If waste

glass is to be returned to the furnaces, impurities must be removed since they may cause erosion of the furnace refractories or alter the color characteristics of the glass.[8] As little as a tenth percent copper or a few tenths percent iron will produce appreciable color in clear glass. While the separation of glass from other refuse is still necessary if it is to be used as aggregate, contamination by non-glass components is not as critical. Laboratory tests have indicated that asphaltic mixtures can be designed to meet requirements for stability, flow and void content using glass separated from municipal refuse and containing up to 17 percent non-glass components.[9] Color separation is not necessary for glass used as aggregate, and transportation costs are minimized since the waste glass can be used in the urban area where it is generated. By substituting glass for portions of the conventional aggregates used in city street construction or maintenance, a steady market would be assured for this waste component.

The diminishing natural aggregate supplies in some urban areas further enhance this concept since aggregate costs increase with increasing haul distances. The depletion of suitable aggregate sources in localized areas and regions has led national highway officials to study promising replacements for conventional aggregates for highway use. The volume of waste glass is small when compared to the amounts of aggregate required for highway construction; consequently, it is not expected that glass will comprise a significant percentage of the aggregate used for this purpose. However, this use has the potential for utilizing all of the waste glass that can be economically separated from refuse in urban areas of the United States.

Development and Resume of the Study

The possibility of using waste glass as an aggregate in asphaltic concrete grew out of a special problem assignment in a ceramic engineering class at the University of Missouri-Rolla. A preliminary assessment of the potential problems which might be encountered included consideration of possible poor adhesion between asphalt and glass in the presence of water, adverse effects of flat and elongated particles on mixture density, low strengths and poor skid resistance due to the smooth surface texture of glass, and increased tire wear due to the sharp, angular particles.

Promising results obtained in pilot tests conducted on asphaltic mixtures containing glass aggregates led to the funding of a research project by the U. S. Public Health Service Bureau of Solid Waste Management. The overall purpose of this project was to determine whether waste glass could be used as an aggregate in asphaltic mixtures for street construction or maintenance and to demonstrate its potential

use as a method for disposing of urban glass waste. The specific objectives were to:

1. Acquire engineering data on glass-asphalt mixtures with respect to suitable particle size ranges for the glass aggregate, proper type and grade of asphalt to be used, and the range of asphalt contents satisfying stability, durability, and workability requirements.

2. Institute a field testing program in which glass-asphalt mixtures would be used in actual paving operations.

3. Compile the information resulting from the study for use in recommending design and construction procedures which permit the effective utilization of waste glass.

Initial mix design studies showed that asphaltic mixtures satisfying standard design criteria could be designed using aggregates composed entirely of glass. However, these mixtures had very poor water resistance due to stripping of the asphalt from the glass particles when specimens were immersed in water. Tests were then conducted to investigate means by which the water resistance could be improved. Commercial anti-stripping agents improved the water resistance to a limited extent, but the most effective additive was hydrated lime. The addition of one percent hydrated lime by weight of the aggregate eliminated stripping in laboratory tests.

Upon learning of our work in evaluating glass-asphalt paving mixtures, Owens-Illinois, Inc. became interested in the project and volunteered to install a small test section at their technical center in Toledo, Ohio. In October of 1969, the first pavement containing glass aggregates was placed by Owens-Illinois and the word "glasphalt" was used to describe the material. The publicity resulting from this first field installation generated wide interest in the concept and since then 19 additional experimental glasphalt pavements have been placed in the United States and Canada. The Glass Container Manufacturers Institute and several member glass companies were instrumental in planning and financing many of these installations, in cooperation with the project staff at the University of Missouri-Rolla. Several state and municipal agencies as well as private industries also became involved in the construction of glasphalt pavements. A current listing of the glasphalt test sections installed during the duration of our research project is given in Table 1. Tests and observations of the performance of these test sections which were subjected to varying types and volumes of traffic and climatic conditions have provided valuable data for assessing the technical feasibility of glasphalt pavements.

Further laboratory testing was also conducted to determine the effects of particle size distribution upon mechanical properties and to compare the abrasiveness of asphaltic mixtures containing glass with mixtures containing conventional aggregates.

Results of laboratory and field tests on asphaltic mixtures containing glass aggregates have demonstrated that acceptable pavements can be constructed using this material. Conventional methods for placing and compaction can be employed and adequate performance has resulted in most installations. Surface deterioration or raveling has occurred on some of the glasphalt pavements, but otherwise the structural performance has been good and the skid resistance has been found to exceed tentative minimum recommended limits.

The potential for using waste glass in asphaltic pavements has been demonstrated and there are no insurmountable technical problems associated with this usage. However, present techniques for recovering glass from refuse impose economic limitations on the successful utilization of this method for re-using the glass. Hand-picking is expensive and even if containers are collected at recycling centers using donated labor, crushing is required. Due to the relatively small volume of glass involved, unit crushing costs are high. Consequently, the economic feasibility of employing waste glass as aggregates will depend on the development of large scale systems for separating refuse into usable components including a glass fraction which could preferably be used in glasphalt with a minimum of further processing.

TABLE 1
GLASPHALT PAVEMENTS PLACED
IN THE UNITED STATES AND CANADA

Location	Size	Thickness	Date Placed	Organization
Toledo, Ohio (plant entrance)	18 x 50 ft.	2-in.	Oct. 4, 1969	Owens-Illinois
Winchester, Ind. (parking lot)	1500 sq. ft.	1½-in.	June 8, 1970	Anchor-Hocking
Rolla, Mo. (campus road)	20 x 525 ft.	1½-in.	July 10, 1970	Univ. of Missouri-Rolla U.S. Env. Protection Agency, GCMI
Bramalea, Canada (truck access road)	18 x 500 ft.	3-in.	Aug. 29, 1970	Dominion Glass Co.
Scarborough, Canada (residential street)	26 x 600 ft.	1-in.	Oct. 17, 1970	Glass Container Council of Canada
Fullerton, California (industrial park street)	30 x 600 ft.	3-in.	Oct. 26, 1970	Glass Container Corporation
Brockway, Pa. (parking lot)	14,400 sq. ft.	1-in. 5-in.	Oct. 28, 1970	Brockway Glass Co.
New Orleans, La. (parking lot)	10,000 sq. ft.	2-in.	Feb. 1, 1971	Louisiana Coca-Cola Company
Des Moines, Iowa (fairgrounds road)	12 x 300 ft.	1-in.	May 15, 1971	Keep Iowa Beautiful State and City Agencies

TABLE 1 (cont.)
GLASPHALT PAVEMENTS PLACED
IN THE UNITED STATES AND CANADA

Location	Size	Thickness	Date Placed	Organization
San Francisco, Calif. (parking lot)	7500 sq. ft.	1½-in.	May 20, 1971	Lucky Lager Breweries
Rolla, Mo. (parking lot)	12,000 sq. ft.	2-in.	May 27, 1971	Univ. of Missouri-Rolla U.S. Env. Protection Agency, GCMI
Burnaby, B.C. (city street)	20 x 700 ft.	1½-in.	June 18, 1971	Municipality of Burnaby Dominion Glass Co.
Big Flats, N.Y. (plant entrance)	9 x 58 ft.	1½-in.	July 6, 1971	Thatcher Glass Co.
Omaha, Nebraska (city street)	60 x 280 ft.	1-in.	Aug. 6, 1971	Keep Nebraska Beautiful City of Omaha
Baltimore, Md. (city street)	6500 sq. ft.	1-in.	Aug. 19, 1971	City of Baltimore
Azusa, California (city street)	40 x 300 ft.	1½-in.	Aug. 1971	Miller Brewing Co. City of Azusa
Holland, Michigan (parking area)	50,000 sq. ft.	1½-in.	Sept. 28, 1971	Brooks Products City & Local Groups
Albuquerque, N. M. (parking lot)	40 x 200 ft.	1½-in.	Sept. 1971	Keep New Mexico Beautiful City Groups

TABLE 1 (cont.)
GLASPHALT PAVEMENTS PLACED
IN THE UNITED STATES AND CANADA

Location		Size	Thickness	Date Placed	Organization
Toledo, Ohio (city street)	Surface course	24 x 1000 ft.	1½-in.	Sept. 1971	Owens-Illinois State of Ohio City of Toledo
	Levelling course	24 x 800 ft.	1½-in.		
	Base course	24 x 600 ft.	3-in.		
	Base course	24 x 600 ft.	9-in.		
	Subgrade	24 x 200 ft.	6-in.		
South Burlington, Vt. (state highway)		22 x 2200 ft.	1-in.	June 1972	Vermont Department of Highways

INITIAL DESIGN STUDIES

Materials

To determine the feasibility of using waste glass as aggregates, initial studies were conducted using mixtures consisting of asphalt and all-glass aggregates. Non-returnable beer and soft-drink bottles were washed to remove labels and other foreign material, dried, and then crushed initially in a jaw crusher followed by final crushing in a roller mill. The crushed glass was dry-sieved into nine size fractions ranging from material passing a 1/2-in. sieve and retained on a 3/8-in. sieve to material passing a No. 200 sieve. A washed sieve analysis was performed on samples from each size fraction and the results were used in combining the fractions to obtain the desired gradation.

The crushed glass contained a relatively large amount of flat and/or elongated particles in nearly all fractions. Samples from several of the larger size fractions were tested for percentage of flat and elongated particles using Corps of Engineers Methods CRD-C 119-53 and CRD-C 120-55. Results of these tests are shown in Table 2.

TABLE 2

SHAPE CHARACTERISTICS OF CRUSHED GLASS USED IN INITIAL DESIGN STUDIES

Sieve Size			Percent in Each Classification			
Passing	Retained	No. Counted	Flat*	Elong.+	Flat and Elong.	Not Flat Or Elong.
1/2-in.	3/8-in.	101	93	0	4	3
3/8-in.	No. 4	117	48	3	2	47
No. 4	No. 8	300	9	19	0	72
No. 8	No. 16	306	25	2	0	73
No. 16	No. 30	305	49	3	1	47

*Width/Thickness greater than or equal to 3.0
+Length/Width greater than or equal to 3.0

The bulk specific gravity of the glass was 2.50, the absorption was virtually zero and the loss in the Los Angeles abrasion test (Gradation C) was 41 percent.

The asphalt used was an 85-100 penetration asphalt cement furnished by the Shell Company. This asphalt was produced from a West Texas crude and had the properties shown in Table 3.

TABLE 3

PROPERTIES OF ASPHALT USED IN INITIAL DESIGN STUDIES*

Specific gravity @ 60°F	1.011
Penetration @ 77°F	92
Viscosity S.S.F. @ 275°F	143.5
Flash, °F, Cleveland open cup	595
Solubility in CCl_4, %w	99.9
Ductility @ 77°F, cm.	150+

*Furnished through courtesy of Shell Oil Company

Test Procedures

Marshall test procedures as specified in ASTM D 1559, were followed with the following exceptions:

1. Immediately after mixing in a Hobart Model N-50 mixer for 3 minutes, the bituminous mixture was placed in the compaction mold and put in an oven maintained at 275F for 30 minutes. It was then removed, spaded, and compacted as specified in ASTM D 1559.

2. In the first trial mix series, rather than immersing the specimens directly in a 140F water bath for 30 minutes prior to testing, they were first placed in a plastic bag and then put in the water bath. This was done in order to prevent surface stripping which would alter the results of mechanical analyses of the extracted aggregate. Some leakage occurred in most of the bags, however, and in the second trial mix series, all specimens were placed in an oven at 140F for 2 hours prior to testing.

After the completion of stability testing, bitumen content was determined using a reflux extractor, and a mechanical analysis of the extracted aggregate was performed using AASHO Method T 30.

Mix Design

The first trial mix utilized aggregate gradation No. 1 shown in Table 4. This gradation has been suggested by Goode and Lufsey[10] for maximum density and is calculated from the relation

$$P = \left(\frac{d}{D}\right)^{0.45} \times 100$$

where P = Percent passing a sieve having an opening of d inches

D = Maximum size of the aggregate
0.45 = An empirical constant

It was realized that the exponent 0.45 for maximum density was based upon reasonably equidimensional particles and thus might not yield maximum density for the flat and elongated glass particles. However, it was taken as a starting point, and modified as noted later.

TABLE 4

GRADATION OF CRUSHED GLASS USED IN INITIAL DESIGN STUDIES

Sieve Size	Percent Passing	
	Gradation No. 1	Gradation No. 2
1/2-in.	100	100
3/8-in.	88	88
No. 4	65	67
No. 8	47	48
No. 16	35	37
No. 30	26	28
No. 50	18	18
No. 100	14	11
No. 200	9.7	6.3

Six asphalt contents were chosen in 0.5 percent increments from 4.5 to 7.0 percent (total weight basis) and five specimens were made for each asphalt content. Six specimens were made each day for 5 days, with one specimen representing each of the six asphalt contents being made each day. A hand operated Marshall compaction hammer was used with 50 blows being applied to each end of the specimen.

Bulk specific gravity of each specimen was determined using ASTM D 2726 - 68T after which the specimens were tested for stability and flow.

Results from this first trial are given in Table 5 and Fig. 1. As can be seen from the graphs in Fig. 1, no asphalt content completely satisfied the Marshall design criteria suggested by The Asphalt Institute and shown in Table 6. While stability and flow were adequate at the lower asphalt contents, air content was above the minimum specified level only at 4.5 percent asphalt and voids in the mineral aggregate were below minimum allowable values at all asphalt contents between 4.5 and 6.0 percent.

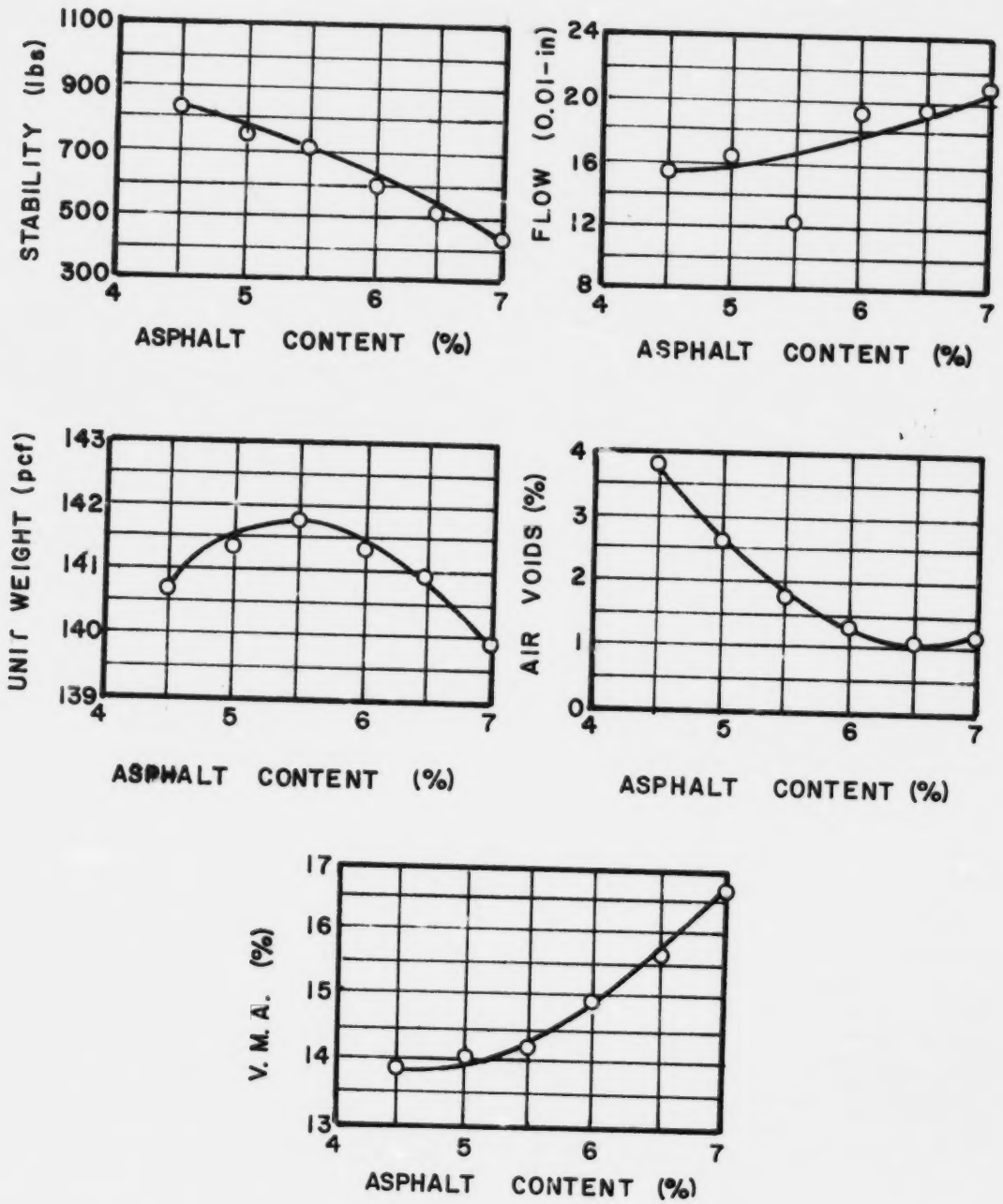

Fig. 1 Marshall Test Properties from Initial Mix Design (Gradation No. 1)

TABLE 5

MARSHALL METHOD DATA FOR INITIAL DESIGN STUDIES*

Asphalt Content	Unit Weight (pcf)	Air Voids (%)	Voids in Mineral Agg. (%)	Stability (lbs.)	Flow (.01-in.)
First Trial Mix - Aggregate Gradation No. 1					
4.5	140.7	3.88	13.89	820	15.8
5.0	141.4	2.67	13.95	744	16.4
5.5	141.7	1.82	14.14	729	12.6
6.0	141.3	1.37	14.85	596	19.4
6.5	140.9	0.98	15.59	536	19.4
7.0	139.9	1.14	16.61	429	20.8
Second Trial Mix - Aggregate Gradation No. 2					
4.0	137.6	6.57	15.36	1061	7.6
4.5	137.9	5.74	15.55	736	7.4
5.0	138.7	4.50	15.57	639	7.4
5.5	139.4	3.39	15.52	767	8.0
6.0	139.5	2.62	15.93	520	10.4
6.5	139.5	1.97	16.44	492	11.0

*All values are averages of 5 specimens

TABLE 6

MARSHALL DESIGN CRITERIA RECOMMENDED BY THE ASPHALT INSTITUTE FOR MEDIUM TRAFFIC

Test Property	Min.	Max.
Stability, lbs.	500	--
Flow, .01-in.	8	18
Air Voids, % (Surfacing)	3	5
Voids in Mineral Aggregate, % (1/2-in. max. size)	15	--

A second series of specimens was molded, using the aggregate gradation No. 2 shown in Table 4. This gradation had less material passing the 100 and 200 sieves. Six asphalt contents were chosen in 0.5 percent increments from 4.0 to 6.5 percent and once again five specimens were made for each asphalt content using 50 blow Marshall compaction.

Results from this second trial are given in Table 5 and Fig. 2. The reduced fines content resulted in higher voids contents and permitted the choice of an asphalt content which satisfied all of the design criteria suggested by The Asphalt Institute.

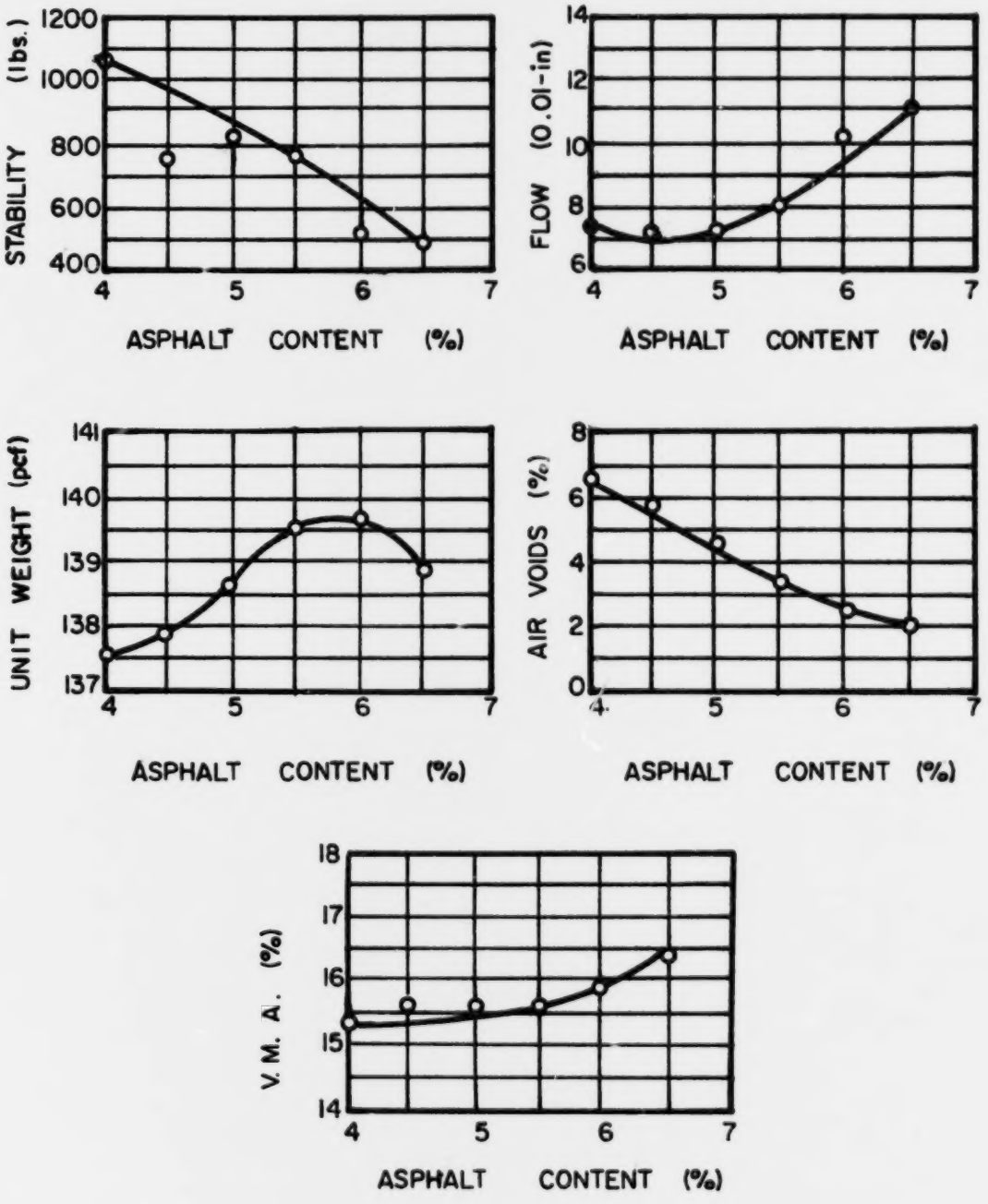

Fig. 2 Marshall Test Properties from Initial Mix Design (Gradation No. 2)

Degradation Studies

One specimen was chosen at random from the five specimens representing each asphalt content for both trial mixes. The asphalt was removed from each of these by use of a reflux extractor with benzene as the solvent. Washed sieve analyses were conducted on the recovered aggregate (AASHO T30) and the results are summarized in Table 7.

TABLE 7

RESULTS OF SIEVE ANALYSES OF EXTRACTED AGGREGATES

First Mix Design Series

Sieve	Uncompacted % Passing	Gradation of Extracted Aggregate % Passing for Indicated Asphalt Content					
		4.5	5.0	5.5	6.0	6.5	7.0
1/2-in.	100	100	100	100	100	100	100
3/8-in.	88	94	94	94	93	92	93
No. 4	65	68	68	69	67	67	66
No. 8	47	49	49	49	49	48	47
No. 16	35	35	36	35	35	34	34
No. 30	26	26	26	26	27	23	25
No. 50	18	18	18	18	19	18	18
No. 100	14	14	14	14	14	13	14
No. 200	9.7	9.0	9.3	8.7	8.9	8.8	9.5
Hudson $\bar{A}$	5.03	5.13	5.14	5.14	5.13	5.04	5.07

Second Mix Design Series

Sieve	Uncompacted % Passing	Gradation of Extracted Aggregate % Passing for Indicated Asphalt Content					
		4.0	4.5	5.0	5.5	6.0	6.5
1/2-in.	100	100	100	100	100	100	100
3/8-in.	88	95	95	94	94	93	92
No. 4	67	69	70	69	70	68	68
No. 8	48	50	50	52	51	51	50
No. 16	37	39	39	38	39	37	39
No. 30	28	28	28	28	28	27	28
No. 50	19	19	19	20	19	18	19
No. 100	11	13	12	13	13	12	12
No. 200	6.3	10.0	6.6	7.6	7.8	6.0	7.8
Hudson $\bar{A}$	5.03	5.23	5.20	5.22	5.22	5.12	5.16

In order to express the degradation which occurred in terms of a single number rather than a multiplicity of percentages, a factor known as the Hudson $\bar{A}$ was calculated. Hudson $\bar{A}$ is a one-hundredth of the sum of the percentages passing the ten U. S. Standard sieves starting with the

1 1/2-in. and including the No. 200 sieve. With asphaltic concrete aggregates in the usual range of $\bar{A}$ from 4.00 to 6.00, a change of 0.50 in the value of $\bar{A}$ would change the asphalt demand by about 1 percent by volume.[11]

The results from the first trial mix indicate that little degradation of the aggregate occurred. There is an anomaly here in the percentages of material passing the No. 200 sieve. As can be seen in Table 7, the percentage of minus 200 mesh material decreased after the specimens had been mixed, compacted and tested for stability. This loss of material was thought to be due to stripping and loss of surface material on the specimens during the period in the water bath prior to testing for stability. However, it was quite apparent that very little new minus 200 mesh material was produced during mixing, testing, and compaction of these specimens and that, in general, degradation was very light as indicated by changes in Hudson $\bar{A}$.

Degradation was more pronounced in the second trial mix series. The Hudson $\bar{A}$ increased by as much as 0.20 and there was a greater percentage increase in the minus 200 mesh material. The fact that more air voids were present indicates that perhaps the asphalt filler matrix was not as effective in cushioning the compactive blows, thus resulting in the formation of more fines.

Water Resistance Studies

Static stripping tests (ASTM 1664) were conducted on several combinations of glass aggregates and asphalt. Stripping was noted in the combination of glass and asphalt cement with no anti-stripping compound added. However, mixtures of glass and either a slow setting cationic emulsion or an asphalt cement with a proprietary anti-stripping compound exhibited no stripping.

One set of six specimens utilizing gradation No. 2 and an asphalt content of 5.5 percent was molded to determine the percentage stability lost after immersion in water at 120F for 4 days. However, stripping was so severe that the specimens disintegrated.

Discussion

The data indicated that a mix satisfying the Marshall design criteria suggested by The Asphalt Institute could be designed using crushed glass aggregates having a modified maximum density gradation.

The aggregate degradation noted in the second trial mix was compared with degradation resulting from field compaction

of conventional asphaltic concrete. Data obtained by Goode and Owings[12] in a laboratory - field study of degradation occurring in hot asphaltic concrete wearing course mixtures was used to obtain values for changes in Hudson $\bar{A}$ associated with field compaction and traffic compaction. Although this parameter was not used in their paper, the data they presented permitted calculation of it for comparison purposes. An increase in the Hudson $\bar{A}$ value of 0.25 due to field compaction and an increase of 0.39 due to field compaction and traffic were both considered to be minor and insufficient to affect the service behavior of the pavement. Since the maximum increase in Hudson $\bar{A}$ noted in our study was 0.20, degradation due to laboratory mixing, compacting, and testing was not considered to be excessive.

Water resistance of the glass-asphalt mixtures was poor and severe stripping occurred when specimens were immersed in water at 140F for 4 days. This indicated a need for developing means to prevent stripping in glass-asphalt mixtures.

WATER RESISTANCE STUDIES

In order to investigate means for improving water resistance, immersion-compression tests (ASTM D 1075) were conducted on specimens containing glass aggregates and several different anti-stripping additives.

Materials

Glass aggregate was produced using the crushing methods previously described in the section on initial mix design. Gradation No. 2 in Table 4, which resulted in a mixture meeting Marshall design requirements suggested by The Asphalt Institute, was used in these studies. The asphalt was an 85-100 penetration asphalt cement produced from a West Texas crude and had the properties shown in Table 3.

Three commercial anti-stripping agents were examined: Pavebond, No-Strip and Dehydro H 86 C. Pavebond is described as a heat-stable coating and bonding agent. No-Strip is a cationic oil-soluble surface active agent which is manufactured by reacting a long chain fatty acid with a short chain amine or polyamine under specific reaction conditions. The molecule thus formed (an amidoamine soap) consists of a polar end containing the acid-amine reaction site and a long hydrocarbon chain non-polar end. Dehydro H 86 C is a modified ester of tall oil and triethanolamine.

Reagent grade calcium hydroxide was also used as an additive since it has been reported to reduce the stripping tendency of certain aggregates,[13] and limestone dust was substituted for the minus 200 mesh glass to determine whether elimination of the very fine glass would reduce stripping.

Test Procedures

Immersion-compression tests were conducted in accordance with ASTM D 1075. Six 4 by 4-in. cylindrical specimens were made for each test in accordance with procedures outlined in ASTM D 1074. An asphalt content of 5.5 percent (total weight basis) was used in the specimens and the commercial anti-stripping agents were added to the asphalt at three addition levels of 1, 2, and 4 percent by weight of the asphalt. Six specimens were molded for each agent and addition level with an additional six specimens containing no anti-stripping agent. After oven-curing, the bulk specific gravity of each specimen was determined and the specimens were then divided into two groups such that the average bulk specific gravity of each group was essentially the same. One group was stored in an oven at 77F for four hours prior to testing. The other group was prepared for testing by immersion in water for 24 hours

at 140F followed by immersion for two hours at 77F. The specimens were each tested in axial compression without lateral support at a uniform rate of vertical deformation of 0.2 in. per minute.

Test Results

The compression test results are shown in Table 8. Specimens containing no anti-stripping agent disintegrated completely when immersed in water at 140F for 24 hours. Addition of the three anti-stripping agents at the 1 percent concentration level resulted in little or no improvement in water resistance. At the 2 percent concentration level, 41 and 47 percent retained strengths were obtained for Pavebond and No-Strip respectively while zero percent retained strength was obtained with Dehydro H 86 C. Only at a 4 percent concentration level was there a significant increase in water resistance. Use of Pavebond at this level resulted in a retained strength of 71 percent and No-Strip produced mixtures with 67 percent retained strength. Dehydro H 86 C resulted in a retained strength of only 32 percent at the 4 percent addition level.

TABLE 8

IMMERSION-COMPRESSION TEST RESULTS
FOR COMMERCIAL ANTI-STRIPPING ADDITIVES

		Dry Specimens			Wet Specimens		
Additive		Air Voids (%)	VMA* (%)	Strength (psi)	Air Voids (%)	VMA* (%)	Strength (psi)
Control (No Additive)		4.91	16.84	50	4.90	16.83	0
Pavebond	1%+	4.92	16.85	58	4.90	16.83	0
	2%	4.75	16.70	68	4.65	16.61	28
	4%	4.70	16.65	48	4.69	16.65	34
No-Strip	1%	4.10	16.14	45	4.00	16.05	0
	2%	4.10	16.13	72	4.11	16.14	34
	4%	3.80	15.87	64	3.81	15.88	43
De-Hydro H 86 C	1%	4.58	16.55	68	4.57	16.54	12
	2%	4.75	16.73	65	4.78	16.73	0
	4%	4.79	16.73	62	4.72	16.68	20

*Voids in Mineral Aggregate
+Percent added by weight of asphalt

Since the commercial anti-stripping agents provided only a borderline improvement in the water resistance, hydrated lime was substituted for the minus 200 mesh glass at three different addition levels. In one set of specimens all of the minus 200 glass was replaced by an equal volume of hydrated lime (5.4% by weight of the aggregate). In a second set 33 percent of the minus 200 glass was replaced by an equal volume of hydrated lime (1.9% by weight of the aggregate) and in a third set approximately 17 percent of the minus 200 glass was replaced by an equal volume of hydrated lime (0.9% by weight of the aggregate). The results of immersion-compression tests on these specimens are shown in Table 9. Replacement of all the minus 200 glass by hydrated lime resulted in 110 percent retained strength while the replacement of 33 percent and 17 percent of the minus 200 glass resulted in 193 and 100 percent retained strength respectively.

Additional tests were conducted in which all of the minus 200 mesh glass was replaced by an equal volume of limestone dust (6.5% by weight of the aggregate). The addition of limestone dust resulted in no improvement in retained strength, as shown in Table 9.

TABLE 9

IMMERSION-COMPRESSION TEST RESULTS
FOR HYDRATED LIME AND LIMESTONE DUST ADDITIVES

	Dry Specimens			Wet Specimens		
Additive	Air Voids (%)	VMA* (%)	Strength (psi)	Air Voids (%)	VMA* (%)	Strength (psi)
Hyd. Lime (5.4%)+	5.75	17.56	150	5.74	17.55	166
(1.9%)	4.95	16.85	67	4.94	16.83	129
(.9%)	5.24	17.11	55	5.24	17.11	55
Lime-stone Dust (6.5%)	3.81	15.93	67	3.83	15.94	0

*Voids in Mineral Aggregate
+Percent added by weight of aggregate

The results of all tests using anti-stripping agents are summarized in Fig. 3. These results show that the use of approximately 1 percent hydrated lime by weight of the aggregate produced a retained strength of 100 percent which was considered to be adequate.

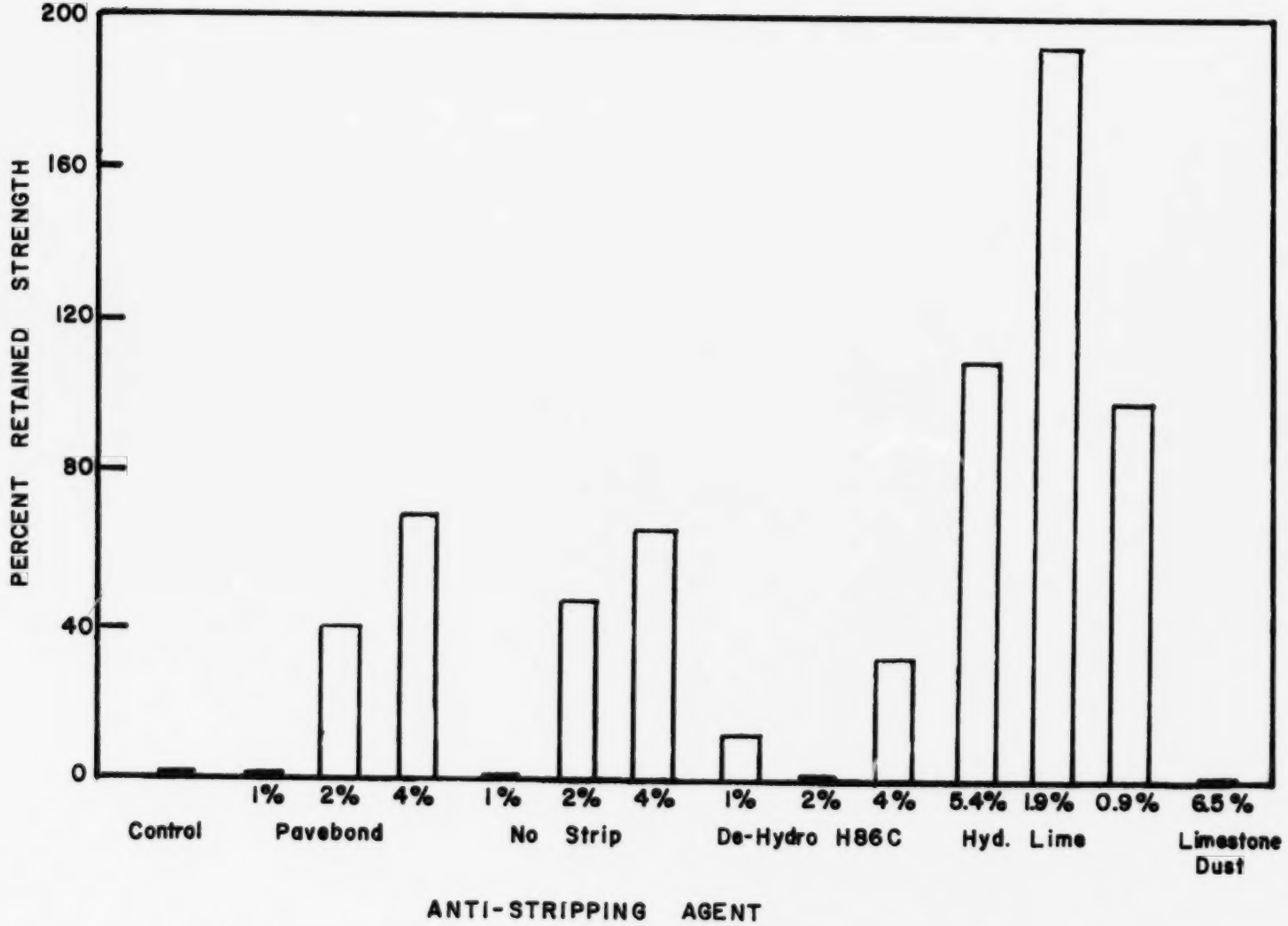

Fig. 3 Effects of Anti-Stripping Agents on Retained Strength

EFFECTS OF PARTICLE SHAPE, ANGULARITY AND GRADATION UPON MIXTURE PROPERTIES

Initial design studies were conducted using the gradations shown in Table 4 which produce maximum density mixtures for nearly equidimensional particles. However, due to the presence of more flat and elongated particles in the glass than would be found in conventional aggregates, a study was conducted to determine the effects of angularity and shape for differing gradations. Dry density tests were conducted on mixtures of glass particles with varying shape and angularity by altering the gradation and noting the effects upon density. Then tests were conducted on asphaltic mixtures with different gradations and particles of varying shape and angularity.

Materials

Glass bottles were crushed in a hammermill and a ball mill was then used to obtain the finer sieve sizes. The crushed glass was separated into nine size fractions ranging from material passing a 1/2-in. and retained on a 3/8-in. sieve to material passing a No. 200 sieve. The percentage of flat and elongated particles in each size fraction was determined using Corps of Engineers Methods CRD-C 119 and CRD-C 120. Results of these determinations are shown in Table 10.

TABLE 10

FLAT AND ELONGATED PARTICLE COUNT FOR CRUSHED BOTTLE GLASS

Sieve Size			Percent in Each Classification			
Passing	Retained	No. Counted	Flat*	Elong.+	Flat and Elong.	Not Flat Or Elong.
1/2-in.	3/8-in.	137	77	1	0	22
3/8-in.	No. 4	224	36	1	0	63
No. 4	No. 8	423	6	0	1	93
No. 8	No. 16	474	9	0	0	91
No. 16	No. 30	303	17	1	0	82
No. 30	No. 50	314	17	1	0	82

*Width/Thickness greater than or equal to 3.0
+Length/Width greater than or equal to 3.0

A mixture of drain cullet and tempered glass was used for glass aggregates with a lower percentage of flat and elongated particles so that shape effects could be investigated. Drain cullet is formed by quenching molten glass in water, forming equidimensional but fairly angular particles.

Tempered glass was crushed to produce equidimensional particles of a finer size than the drain cullet. Crushed tempered glass particles retained on the No. 4 and No. 8 sieves were virtually free of flat and elongated particles but finer sizes of the tempered glass did not differ appreciably from the crushed bottle glass. The flat and elongated particle counts for drain cullet and tempered glass are given in Table 11.

TABLE 11

FLAT AND ELONGATED PARTICLE COUNT
FOR DRAIN CULLET AND CRUSHED TEMPERED GLASS

Sieve Size			Percent in Each Classification			
Passing	Retained	Counted	Flat*	Elong.+	Flat and Elong.	Not Flat Or Elong.
1/2-in.	3/8-in.	102	0	0	0	100
3/8-in.	No. 4	107	0	2	0	98
No. 4	No. 8	313	0	1	0	99
No. 8	No. 16	370	12	0	0	88

*Width/Thickness greater than or equal to 3.0
+Length/Width greater than or equal to 3.0

Glass spheres were used for aggregates with no flat or elongated particles and no angular particles. The spheres ranged in size from 3/8-in. to minus No. 200 mesh material.

The asphalt used in this portion of the investigation was an 85-100 penetration asphalt cement with properties shown in Table 12.

TABLE 12

PROPERTIES OF ASPHALT*

Specific gravity @ 60F	1.011
Penetration @ 77F	90
Viscosity S.S.F. @ 275F	143.5
Flash, ^{o}F, Cleveland Open Cup	590
Solubility in CCl_4, %W	99.93
Ductility @ 77F, cm.	150+

*Furnished through courtesy of Shell Oil Company

Reagent grade hydrated lime was added to the glass-asphalt mixtures in an amount equal to 1 percent by weight of the glass in order to minimize stripping.

Dry Density Tests on Glass Aggregates

The interrelationship between gradations giving maximum density and particle shape and angularity was studied by formulating differing gradations through use of the formula:

$$P = (\frac{d}{D})^n$$

P is the cumulative percent passing a sieve having an opening of size d for an aggregate having a maximum size of D. The grading ratio, n, is the slope of the gradation curve on a double log plot of sieve size versus percent passing. This grading ratio was varied from 0.3 to 0.55 to produce differing gradations and dry density tests were conducted for each gradation so that density and percent voids could be computed. Aggregates with each gradation investigated were thoroughly mixed and placed in a 0.1 cu. ft. measure on a spring mounted platform with an attached mechanical vibrator. The measure was vibrated for 30 seconds while keeping it full to overflowing. Excess material was leveled off and the aggregate was weighed. This procedure was repeated three times to obtain an average dry density.

The first series of tests was conducted using crushed container glass and the grading ratio was varied from 0.3 to 0.55 in increments of 0.025. The plots of density and void content versus grading ratio are shown in Figs. 4 and 5. Maximum density occurred at a grading ratio of about .375 although the curve was quite flat in the region between .325 and .375.

When a similar set of tests was conducted using glass spheres, maximum density occurred at a grading ratio of 0.475 as seen in Figs. 4 and 5. The more nearly equidimensional shape and absence of angularity resulted in higher densities and changed the value of grading coefficient at which maximum density occurred.

Tests conducted using drain cullet and tempered glass resulted in a maximum density gradation at a grading ratio of 0.40, with densities of the same order of magnitude as those obtained with container glass (Figs. 4 and 5). Thus, the effect of using more nearly equidimensional particles without changing the angularity was to increase the grading coefficient giving maximum density.

These test results show that a lower grading ratio is necessary in order to produce maximum density gradations with container glass aggregates.

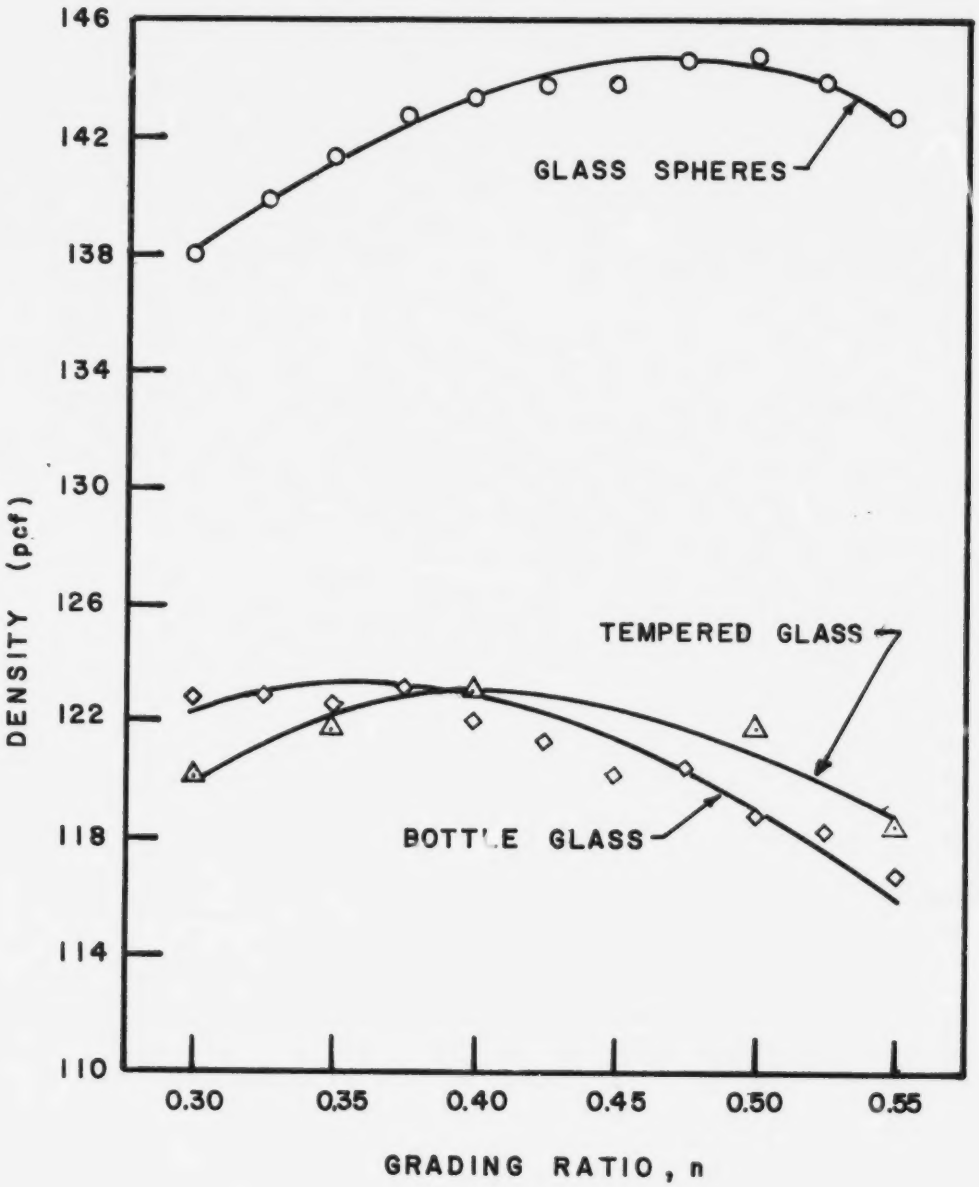

Fig. 4 Bulk Density Resulting from Variable Grading Ratios for Glass Aggregates

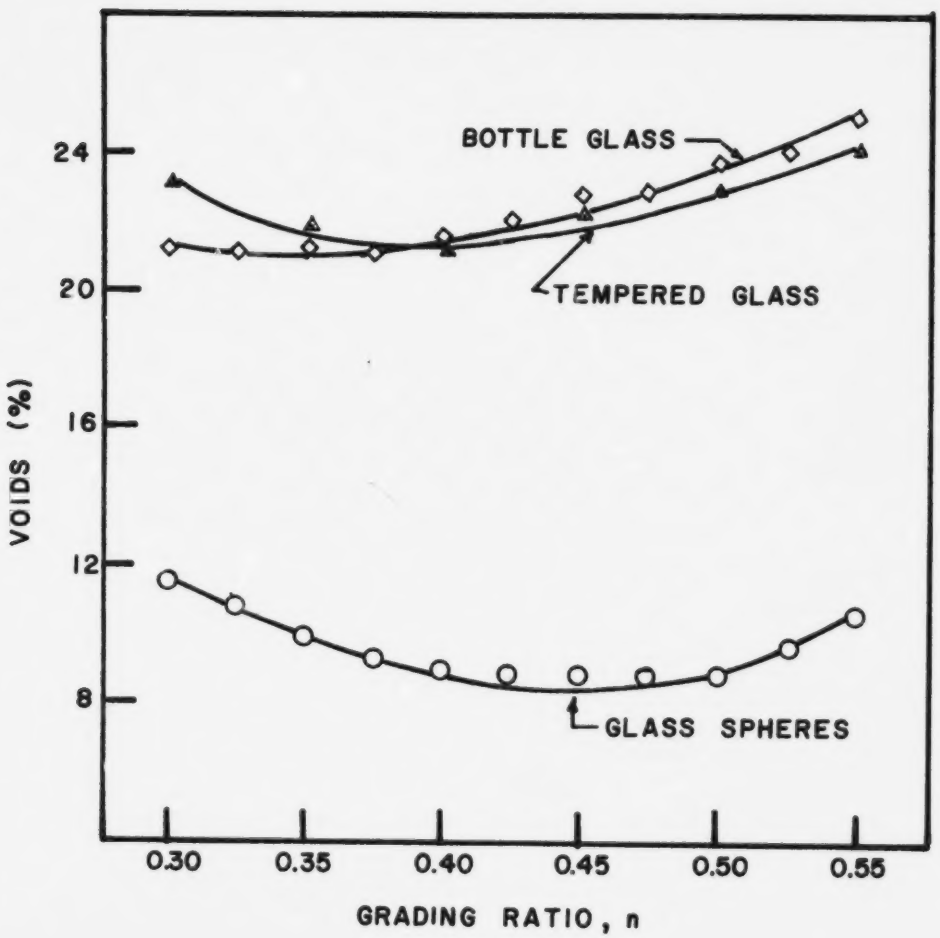

Fig. 5 Void Contents Resulting from Variable Grading Ratios for Glass Aggregates

Effects of Variations in Gradation Upon Marshall Properties of Glass-Asphalt Mixtures

Since maximum bulk density was obtained with the container glass aggregates at a gradation coefficient of 0.375, Marshall test specimens were molded using this gradation (Table 13) and asphalt contents ranging from 4.0 to 6.0 percent in 0.5 percent increments on a total weight basis. According to the results shown in Fig. 6, there was no asphalt content meeting all of the requirements for Marshall properties suggested by The Asphalt Institute. Air voids and voids in the mineral aggregate were low.

Lefebvre[14] suggested three methods for increasing the percentage of voids in the mineral aggregate:

a. Increasing the percentage of fine aggregates.
b. Increasing the percentage of intermediate sizes in the fine aggregate.
c. Decreasing the percentage of mineral filler.

Several modifications in the gradation were made as shown in Table 13 for specimens with an asphalt content of 4.5 percent and the results are given in Table 14. The first modification consisted of reducing the minus 200 mesh material by 4 percent and increasing the material retained on the No. 8 sieve. This change resulted in lower air voids and voids in the mineral aggregate. Reducing the minus 200 mesh material and increasing the plus 30 and plus 100 mesh material in trial 2 also decreased the air voids and VMA. Since the dry density tests had indicated that higher voids were obtained with an exponent of 0.55, Marshall specimens were molded using this gradation, shown for trial 3. However, the air voids and VMA again decreased with this change. This indicated that the dry density is not necessarily related to the density obtained for asphalt mixtures.

In trial 4, minus 200 mesh material was reduced by 9 percent and the amount of intermediate sized fine aggregate was increased. This resulted in acceptable air voids but the VMA was low. Increasing the asphalt content to 5 percent increased the VMA to a value slightly below the acceptable 15 percent value at an air void content of 3.85 percent. However, when the asphalt content was increased to 5.5 percent so that VMA values were high enough, air voids and stability both dropped below acceptable limits.

In trial mix 5 the amount of coarse aggregate and mineral filler was decreased while the amount of intermediate sized aggregate was increased. This resulted in marked increases in air voids and VMA while stability was decreased to an unacceptably low value. This gradation was further modified as shown for trial mix 6 by increasing the amount of coarse aggregate. Specimens were molded at six different asphalt contents ranging from 3.5 to 6.0 percent by weight using this gradation with the results shown in Fig. 7. At an

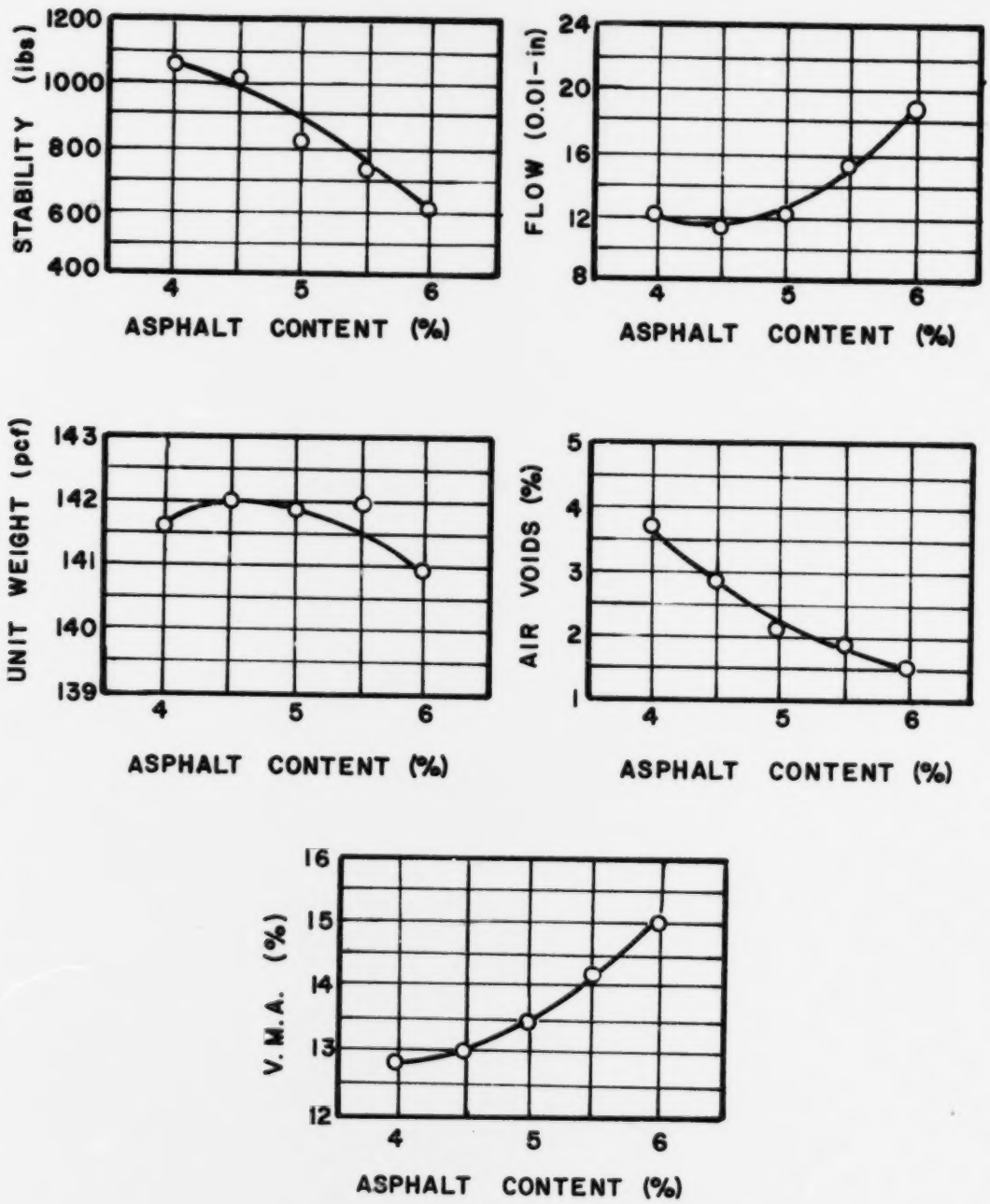

Fig. 6 Marshall Test Properties of Glasphalt with Maximum Bulk Density Gradation (n = .375)

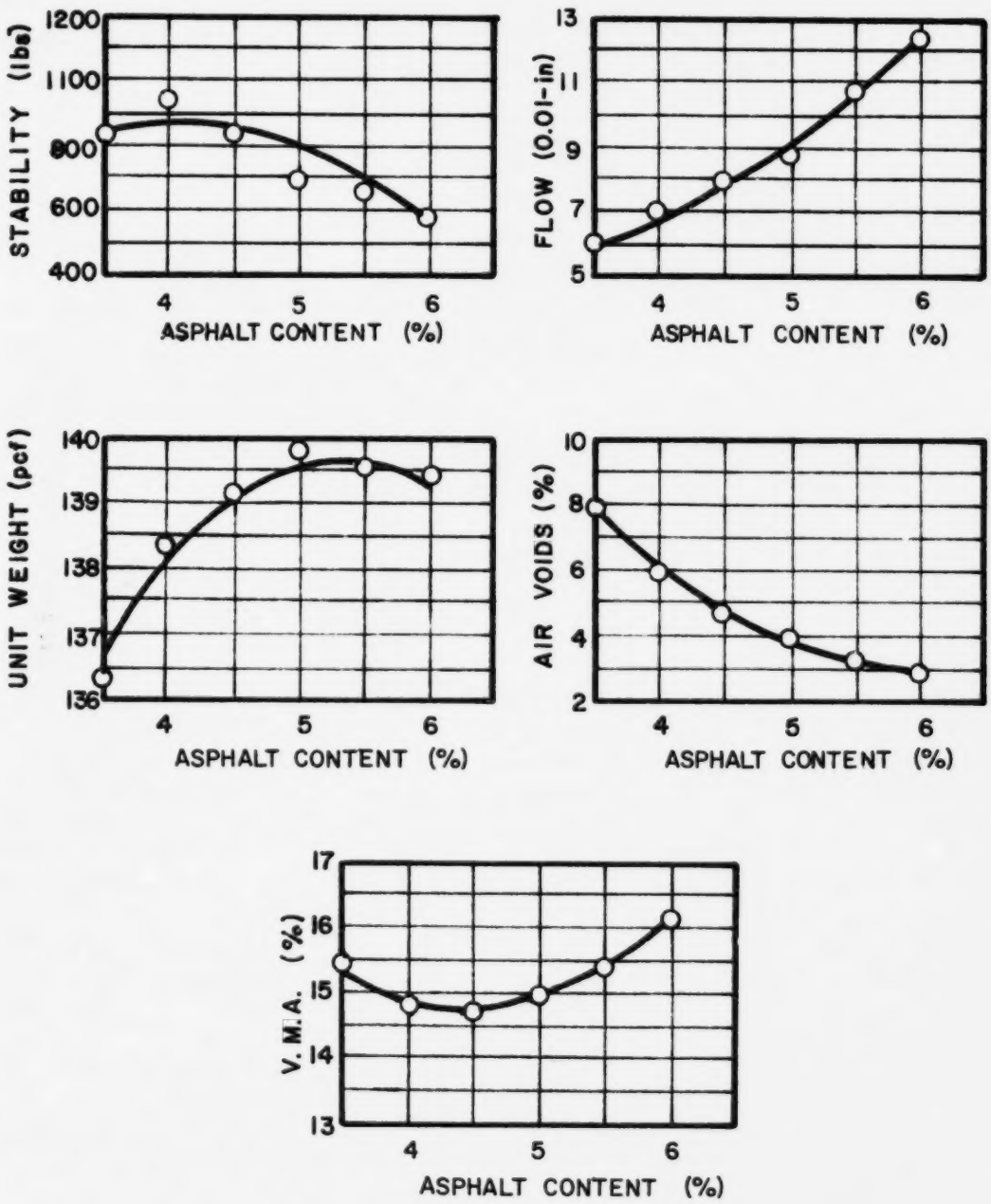

Fig. 7 Marshall Test Properties of Glasphalt with Modified Maximum Bulk Density Gradation

asphalt content of 5.25 percent, the mixture satisfied Marshall design requirements for medium traffic. However, there was little improvement in stability over the original design using a modified gradation with the 0.45 exponent. Consequently, although higher densities did produce larger stability values, the low air voids for the high density mixtures made them unacceptable. Thus it is recommended that the same gradation ranges specified for asphaltic concretes employing conventional aggregates be used for glasphalt mixtures. Typical gradations specified for conventional aggregate are given in Introduction to Asphalt,[15] published by The Asphalt Institute.

Effects of Angularity and Sphericity of Aggregates on Marshall Properties

The effects of angularity and sphericity of aggregates on Marshall properties were determined from specimens made using gradation number 6 in Table 13 and an asphalt content of 5.25 percent. The four different combinations of glass used are shown in Table 15. Mixes A, B, and C all contained crushed container glass in sizes smaller than a No. 8 sieve, but container glass coarse aggregate was used in Mix A, drain cullet and tempered glass coarse aggregate were used in Mix B, and glass spheres were used as coarse aggregate in Mix C. The aggregate for Mix D consisted entirely of glass spheres. Three specimens were molded and tested for each aggregate combination and the results are shown in Table 16.

Substitution of the more nearly equidimensional drain cullet and tempered glass for coarse bottle glass particles caused a slight increase in air voids and VMA with a slight decrease in stability. When glass spheres were substituted for the coarse container glass, air voids and VMA decreased, but there was also a substantial decrease in stability. The decrease in stability was probably due to a reduction in the interlocking resistance developed between the coarse particles. This effect was even more pronounced when container glass was replaced by glass spheres in all sizes, with the specimens having virtually zero stability and a higher air void content. This mixture was very difficult to compact since it rebounded after each blow of the compaction hammer.

To further assess the effects of angularity and sphericity of coarse particles, a second series of tests was made using a gradation containing a higher percentage of material coarser than the No. 8 sieve. The gradation computed with an exponent of 0.55 (Table 13, Trial 3) was used at an asphalt content of 5.25 percent and mixtures with crushed container glass, drain cullet and tempered glass, and glass spheres were compared. Substitution of drain cullet for container glass had little effect upon air voids and VMA and decreased stability only slightly. Glass spheres in the coarse fraction once again reduced air voids and VMA and resulted in a significant decrease in stability.

The large percentage of flat and elongated particles in the coarse fraction of the crushed container glass aggregates had little effect upon the Marshall properties of the glass-asphalt mixtures, since the substitution of more nearly equi-dimensional particles in the coarse sizes did not improve the stability and there was little change in void content or flow. The results show that particle angularity, however, has a pronounced effect on stability with less angular particles producing lower stabilities. Thus the large percentage of flat particles in the coarse fraction of glass aggregates should not be a problem with respect to their effects upon Marshall properties, and the angularity of these particles is beneficial to the stability of the mixture. Spherical glass particles should be avoided due to the adverse effect upon stability, but since little if any of a crushed waste glass fraction is likely to contain spherical particles, a restriction on such particles should not create any difficulties in producing glass aggregates.

TABLE 13

MODIFICATIONS IN GRADATION USED FOR
MARSHALL SPECIMENS CONTAINING CRUSHED BOTTLE GLASS

Sieve Size	Percent Passing Given Sieve for Gradations					
	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 6
1/2-in.	100	100	100	100	100	100
3/8-in.	90	90	85	90	92	91
No. 4	69	69	58	69	73	71
No. 8	50	54	41	54	60	57
No. 16	38	42	28	42	48	45
No. 30	28	30	18	28	32	30
No. 50	20	22	13	18	20	19
No. 100	15	15	9	9	9	9
No. 200	10	11	6	5	5	5

TABLE 14

RESULTS OF MARSHALL TESTS
ON SPECIMENS WITH MODIFIED GRADATION

Trial No.	Test Properties*					
	Asphalt Cont.-TWB+ (%)	Unit Weight (pcf)	Air Voids (%)	VMA± (%)	Stability (lbs)	Flow (.01-in.)
1	4.5	142.7	2.34	12.59	920	12
2	4.5	142.8	2.23	12.49	1095	9.5
3	4.5	142.6	2.43	12.67	750	8.7
4	4.5	139.8	4.31	14.37	620	7.8
4	5.0	139.6	3.85	14.93	565	8.7
4	5.5	140.1	2.84	15.02	460	9.8
5	4.5	135.2	7.44	17.16	310	6.2

*Average of three specimens
+Total weight basis
±Voids in Mineral Aggregate

TABLE 15

COMPOSITION OF GLASS-ASPHALT MIXTURES
USING GLASS AGGREGATES OF VARYING SHAPE AND ANGULARITY

Sieve Size		Type of Glass Aggregate for Mix			
Passing	Retained	A	B	C	D
1/2-in.	3/8-in.	Bottle Glass	Drain Cullet	Glass Spheres	Glass Spheres
3/8-in.	No. 4	Bottle Glass	Temp. Glass	Glass Spheres	Glass Spheres
No. 4	No. 8	Bottle Glass	Temp. Glass	Glass Spheres	Glass Spheres
No. 8	No. 16	Bottle Glass	Bottle Glass	Bottle Glass	Glass Spheres
No. 16	No. 30	Bottle Glass	Bottle Glass	Bottle Glass	Glass Spheres
No. 30	No. 50	Bottle Glass	Bottle Glass	Bottle Glass	Glass Spheres
No. 50	No. 100	Bottle Glass	Bottle Glass	Bottle Glass	Glass Spheres
No. 100	No. 200	Bottle Glass	Bottle Glass	Bottle Glass	Glass Spheres
No. 200	PAN	Bottle Glass	Bottle Glass	Bottle Glass	Glass Spheres

TABLE 16

MARSHALL PROPERTIES OF GLASS-ASPHALT MIXTURES
CONTAINING GLASS AGGREGATES OF VARYING SHAPE AND ANGULARITY

Gradation+	Aggregate Combination±	Test Properties*					
		Asphalt Cont-TWB (%)	Unit Weight (pcf)	Air Voids (%)	VMA (%)	Stability (lbs.)	Flow (.01-in.)
Trial 6	A	5.25	138.1	4.57	16.06	590	8.3
Trial 6	B	5.25	137.8	4.79	16.26	560	8.7
Trial 6	C	5.25	141.3	3.89	15.66	415	9.5
Trial 6	D	5.25	140.9	6.82	18.54	---	---
Trial 3	A	5.25	142.4	1.57	13.42	705	12.2
Trial 3	B	5.25	142.5	1.52	13.38	660	14.3
Trial 3	C	5.25	146.6	1.13	13.32	435	17.0

*Average of three specimens
+See Table 13
±See Table 15

FIELD EXPERIENCE WITH GLASS-ASPHALT PAVEMENTS

Asphaltic concrete pavements utilizing glass aggregates have been placed at several locations in the United States and Canada. In all of these installations, glass has been blended with conventional aggregates with varying percentages of glass being used. Design and performance data for several of these pavements are as follows.

University of Missouri-Rolla

A road to the University general services building and central receiving area was paved with glasphalt on July 10, 1970. Traffic density on this road is approximately 700 vehicles per day with 10 percent heavy trucks. The portion paved was 525 feet long and 20 feet wide with a thickness of 1 1/2 inches. It was placed over an existing surface treatment in which chuck-holes had been patched with cold mix prior to tacking with a diluted SS-1 emulsion.

The glass used for this project was donated by member companies of the Glass Container Manufacturers Institute and was a relatively coarse mixture of drain cullet and clean broken bottle glass. The mix was designed to include 63 percent glass, 33 percent fine sand and 4 percent hydrated lime yielding the combined gradation shown in Table 17. While only 1 percent hydrated lime is necessary to provide adequate water resistance, 4 percent was used because the fine aggregate employed in the mixture did not contain enough minus 200 mesh material and only two cold bins were available so that a third aggregate could not be blended into the mixture. Thus, the hydrated lime was used as a source of fines as well as an anti-stripping agent. Results of Marshall design testing with this mixture using an 85-100 penetration asphalt cement are shown in Table 18.

During construction, the material was mixed in a batch plant at 275F with an asphalt content of 5.75 percent (total weight basis). Aggregate gradation based upon hot bin analysis is given in Table 19. After placing half of the pavement the supply of coarse glass was nearly exhausted and the gradation was modified as shown in Table 20. This gradation with an asphalt content of 5.5 percent was used for the remainder of the paving operation. Marshall properties of laboratory compacted field samples for both mixtures are given in Table 21.

TABLE 17

AGGREGATE GRADATION FOR DESIGN STUDIES
OF ROLLA GLASPHALT

Sieve	Percent Passing			
	Coarse Glass	Int. Glass	Sand	Combined Gradation 30% Coarse Glass, 33% Int. Glass, 33% Sand, 4% Hyd. Lime
1/2-in.	93	100	100	97.9
3/8-in.	73	100	100	91.9
No. 4	34	77	100	72.6
No. 8	13	27	100	49.8
No. 16	6	9	91	38.8
No. 30	0	4	71	28.7
No. 50	0	2	34	15.9
No. 100	0	1	6	7.3
No. 200	0	1	0	4.3

TABLE 18

LABORATORY MARSHALL MIX DESIGN RESULTS
FOR ROLLA GLASPHALT

Marshall Properties	Asphalt Content (TWB), %		
	5.0	5.5	6.0
Stability, lbs	825	710	650
Flow, .01-in.	7.9	8.8	10.1
Unit Weight, pcf	139.8	140.5	140.0
Air Voids, %	3.71	3.24	2.80
VMA, %	14.79	15.48	16.08

TABLE 19

COARSE MIXTURE GRADATION BASED ON HOT BIN ANALYSIS FOR ROLLA GLASPHALT

Sieve	Percent Passing			
	Bin 3 260 lbs	Bin 2 770 lbs	Bin 1 680 lbs	Combined Gradation
3/4-in.	100			100.0
1/2-in.	92			98.5
3/8-in.	63.5	100		93.1
No. 4	17	78	100	75.1
No. 8	3.5	31.5	88.5	49.4
No. 16	0.5	19	72	38.0
No. 30	0	14.5	56.5	30.4
No. 50	0	6	24	15.1
No. 100	0	1	3.5	5.8
No. 200	0	0.5	1	4.6

*Includes 75 lbs hydrated lime with 100% passing No. 100 sieve

TABLE 20

FINE MIXTURE GRADATION BASED ON HOT BIN ANALYSIS FOR ROLLA GLASPHALT

Sieve	Percent Passing			
	Bin 3 40 lbs	Bin 2 980 lbs	Bin 1 790 lbs	Combined Gradation
3/4-in.	100			100.0
1/2-in.	92			99.8
3/8-in.	63.5	100		99.3
No. 4	17	78	100	86.9
No. 8	3.5	31.5	88.5	57.7
No. 16	0.5	19	72	44.1
No. 30	0	14.5	56.5	35.2
No. 50	0	6	24	17.2
No. 100	0	1	3.5	6.0
No. 200	0	0.5	1	4.6*

*Includes 75 lbs hydrated lime with 100% passing No. 200 sieve

TABLE 21

MARSHALL PROPERTIES OF FIELD SAMPLES
FOR ROLLA GLASPHALT

Marshall Property	Coarse Mixture	Fine Mixture
Stability, lbs	840	710
Flow, .01-in.	13	8
Unit Weight, pcf	141.5	139.1
Air Voids, %	2.01	4.20
VMA, %	14.88	16.34

A conventional paver and 2 ton roller were used for placing and compaction. Both mixtures were tender and it was necessary to defer breakdown rolling until the mixture temperature had dropped to 225F. The finished pavement, immediately after placing, is shown in Fig. 8.

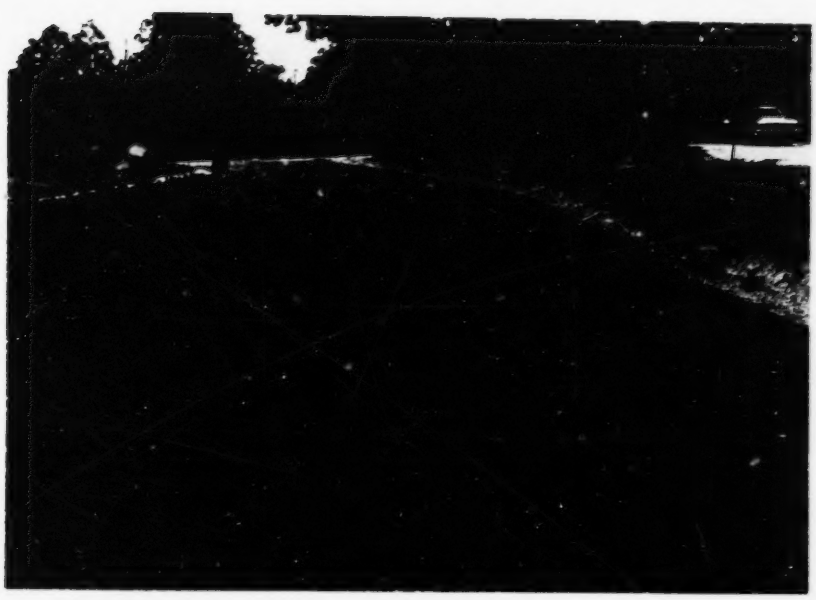

Fig. 8 Rolla Glasphalt Road Immediately after Placement

Sawed samples of the compacted pavement were taken 3 days after compaction and at one year intervals thereafter. The results of density determinations for these samples are given in Table 22. After extracting the asphalt from the samples, washed sieve analyses were conducted on the aggregate. Results are shown in Table 23.

TABLE 22

RESULTS OF DENSITY TESTS FOR ROLLA GLASPHALT

	Coarse Sample		Fine Sample	
	Density	% Comp.	Density	% Comp.
Plant sample (50 blow comp.)	2.268	--	2.229	--
After paving	2.203	97.1	2.178	97.7
After 1 yr	2.204	97.2	2.189	98.2
After 2 yrs	2.224	98.0	2.190	98.2

TABLE 23

RESULTS OF SIEVE ANALYSES OF ROLLA GLASPHALT SAMPLES

	Percent Passing			
Sieve	Plant Sample	After Compaction	After 1 yr.	After 2 yrs.
		Coarse Mixture		
3/4-in.	100	100	100	100
1/2-in.	99.1	99.1	99.6	99.2
3/8-in.	93.0	95.2	96.7	96.1
No. 4	76.1	79.0	78.0	78.1
No. 8	51.1	55.2	56.4	56.4
No. 16	38.8	40.4	40.4	39.6
No. 30	29.4	30.1	30.8	30.3
No. 50	14.0	14.7	15.0	15.3
No. 100	5.6	5.5	5.8	6.2
No. 200	4.0	3.8	4.4	4.9
Hudson's $\bar{A}$	5.12	5.19	5.27	5.27
		Fine Mixture		
3/4-in.	100	100	100	100
1/2-in.	99.4	99.6	99.7	99.5
3/8-in.	96.7	98.2	98.3	97.5
No. 4	84.9	85.8	86.0	86.9
No. 8	60.0	61.1	61.8	63.2
No. 16	43.2	46.2	45.5	46.9
No. 30	33.5	37.0	35.8	37.6
No. 50	15.6	17.7	17.6	17.6
No. 100	5.0	4.5	4.9	5.9
No. 200	3.9	4.0	4.1	4.3
Hudson's $\bar{A}$	5.43	5.54	5.54	5.60

A British Portable Skid Tester was used to measure the skid resistance of the pavement at approximately 1 to 3 month intervals for the first year and at approximately 6 month intervals thereafter. Measurements were made in the wheel tracks at 10 different places for each mixture and variations in the average British Pendulum number with time are shown in Fig. 9.

The pavement surface is in good condition after two years of service as shown in Figs. 10 and 11. Alligator cracking has occurred in one limited area, Fig. 12, but this is due to a base failure.

Glass Containers Corporation

A street in the Fullerton Air Industrial Park in Fullerton, California, was paved with glasphalt on October 26, 1970. The street was 600 feet long and 40 feet wide. Thirty feet of the width was paved with a 3-in. thick layer of glasphalt with the other 10 feet of width being paved with conventional asphaltic concrete. The base course was a 7 1/2-in. thick layer of crushed rock equivalent to California Division of Highways Class 2 aggregate base. The subgrade was a silty sand which had been compacted to at least 90 percent of maximum density as determined in the laboratory in accordance with the requirements of the California Standard Specifications.

All of the glass used for this project was obtained by crushing clean non-returnable bottles in a hammermill. The glass was blended with rock dust and hydrated lime as shown in Table 24 to produce a California 1/2-in. medium gradation. The mixture of 63 percent glass, 36 percent rock dust and 1 percent hydrated lime was used in the mix design with an 85-100 penetration asphalt cement, yielding the results shown in Table 25 for 75 blow compaction.

The design asphalt content chosen was 5.5 percent (total weight basis) with a 60-70 penetration asphalt cement being used at the batch plant rather than the 85-100 penetration material used in the design studies. The composition of the mixture based on hot bin analyses is shown in Table 26. Results of Marshall tests on a sample taken at the plant are given in Table 27.

The material was mixed in a batch type plant with a 4000 lb pugmill and the hydrated lime was added by hand at the pugmill. The 3-in. thick layer was placed and compacted with an 8-10 ton tandem roller. Initial attempts at compaction resulted in excessive crawl even at temperatures of 220F. Breakdown rolling was carried out at temperatures of 220F and below. Appearance of the pavement after compaction is shown in Fig. 13.

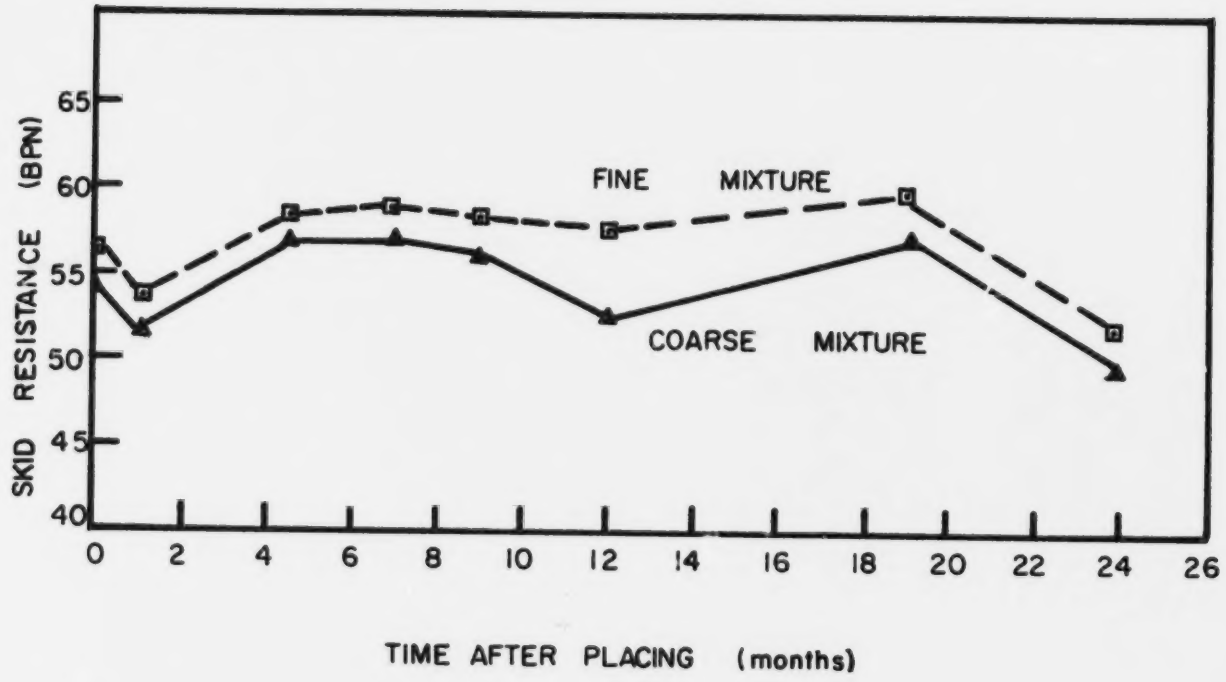

Fig. 9 Variations in Skid Resistance with Time for Rolla Glasphalt Road

Fig. 10 Rolla Glasphalt Road after Two Years of Service

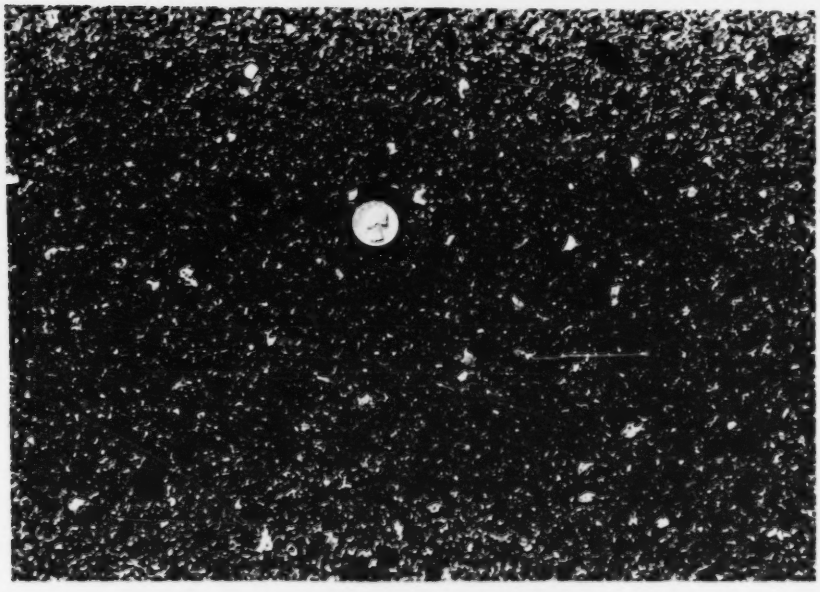

Fig. 11 Surface Texture of Rolla Glasphalt after Two Years of Service

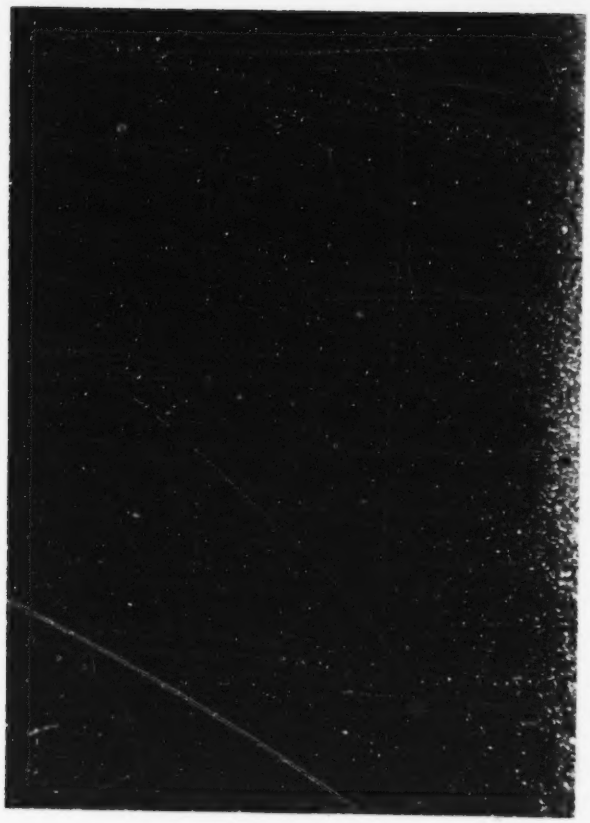

Fig. 12 Alligator Cracking in Localized Area of Rolla Glasphalt Road

TABLE 24

AGGREGATE GRADATION FOR DESIGN STUDIES OF FULLERTON GLASPHALT

Sieve	Percent Passing			
	Glass	Rock Dust	Hyd. Lime	Combined Gradation 63% Glass, 36% Rock Dust, 1% Hyd. Lime
3/4-in.	100			100
1/2-in.	94.5			96.5
3/8-in.	83			89.3
No. 4	51	100		69.1
No. 8	28	89		50.6
No. 16	14	72		35.7
No. 30	6.5	54		24.5
No. 50	3.5	37.5	100	16.7
No. 100	2	24	95	10.8
No. 200	1	15.5	89	7.1

TABLE 25

MARSHALL MIX DESIGN RESULTS FOR FULLERTON GLASPHALT

Marshall Properties	Asphalt Content (TWB), %				
	4.6	5.0	5.4	5.8	6.2
Stability, lbs	830	960	1070	1145	1010
Flow, .01 in.	.10	10.5	11	11.5	12.5
Unit Weight, pcf	138.7	139.2	140.2	140.5	140.7
Air Voids, %	6.8	6.0	4.8	4.1	3.5
VMA, %	16.5	16.6	16.3	16.6	16.8

TABLE 26

GRADATION BASED ON HOT BIN ANALYSIS
FOR FULLERTON GLASPHALT

	Percent Passing				
Sieve	Bin 3 710 lbs	Bin 2 950 lbs	Bin 1 2080 lbs	Hyd. Lime 50 lbs	Combined Gradation
1-in.	100				100.0
3/4-in.	96				99.2
1/2-in.	60.5				92.6
3/8-in.	29	100			86.2
No. 4	3.5	39	100		66.6
No. 8	2	4.5	93.5		54.2
No. 16	1.5	1	52		30.5
No. 30	1	0.5	29.5		17.8
No. 50	0.5	0.5	19.5	100	12.2
No. 100	0.5	0.5	13	95	8.5
No. 200	0.5	0	9.5	85	6.4

Calculated asphalt content - 5.5% (210 lbs)
Asphalt content by extraction - 5.15%

TABLE 27

MARSHALL PROPERTIES FOR
PLANT SAMPLE OF FULLERTON GLASPHALT

Stability, lbs	1770
Flow, .01-in.	13.5
Unit Weight, pcf	140.5
Air Voids, %	4.9
VMA, %	15.9
Stability, lbs (24 hour immersion at 140F)	1610
Retained Stability, %	92.1

Tests conducted on cores removed from the compacted pavement indicated a unit weight of 131.4 pcf or 93.5 percent compaction as shown in Table 28. This low unit weight is believed to be due to the difficulties in compacting the mixture at temperatures above 220F. Table 28 also shows that little further increase in density had occurred after one year when additional cores were obtained. Aggregate gradations based upon wet sieve analyses of the cores after extraction are shown in Table 29.

TABLE 28

RESULTS OF DENSITY TESTS FOR FULLERTON GLASPHALT

	Density	Percent Compaction
Plant Sample (75 blow comp.)	2.252	----
After paving	2.106	93.5%
After 1 yr	2.112	93.8%

TABLE 29

RESULTS OF SIEVE ANALYSES OF FULLERTON GLASPHALT SAMPLES

	Percent Passing		
Sieve	Plant Sample	After Compaction	After 1 yr.
3/4-in.	99.4	98.5	99.6
1/2-in.	94.7	95.2	95.3
3/8-in.	80.6	85.1	84.4
No. 4	54.7	61.1	64.9
No. 8	44.8	48.2	52.7
No. 16	30.7	32.1	34.4
No. 30	20.2	20.7	21.6
No. 50	13.3	14.3	14.2
No. 100	8.5	9.6	9.1
No. 200	5.4	6.4	6.2
Hudson's $\overline{A}$	4.58	4.76	4.87

On March 2, 1971, skid tests were conducted on the glasphalt pavement by the California Division of Highways. The towed trailer method (ASTM E-274) was used at a test speed of 25 mph and the skid number at 25 mph ranged from 61 to 69 which converts to 54 to 62 at 40 mph.

After one year of service, the pavement surface exhibited some raveling caused by the fracture of larger glass particles

at the surface. However, the overall condition of the surface was good as shown in Fig. 14, and its performance has been considered to be satisfactory.

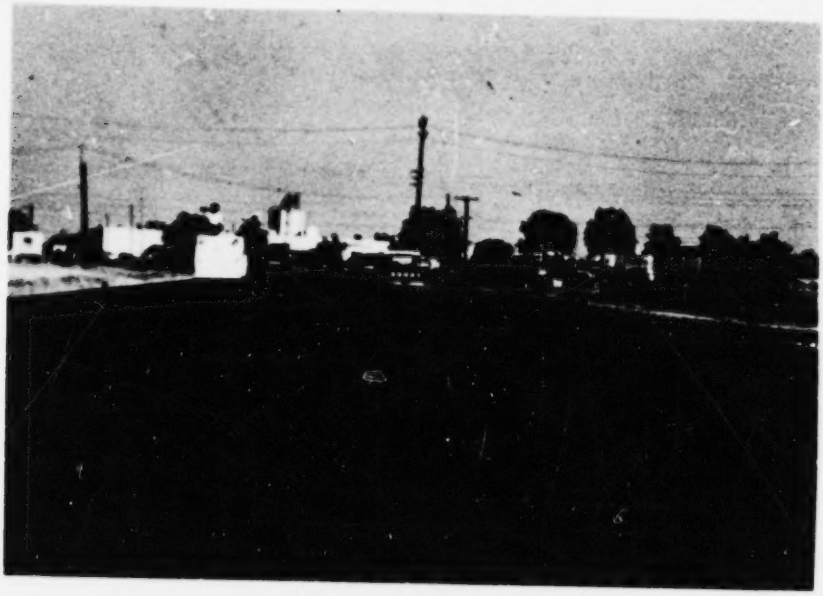

Fig. 13 Fullerton Glasphalt Road Immediately after Placing

Fig. 14 Surface Texture of Fullerton Glasphalt Road after One Year of Service

Bramalea, Ontario

A private road at the Dominion Glass Company's Bramalea, Ontario, plant was paved with glasphalt on August 29, 1970. The roadway width paved was 18 feet and the length was approximately 500 feet. The mix was placed in two courses, each of 1 1/2-in. compacted thickness, giving a total compacted thickness of 3 inches.

Design and testing of the paving was carried out by the Ontario Department of Highways (now Ministry of Transportation and Communication) and the following description of the project is abstracted from their report.[16]

Glass bottles for the project were crushed in a Pioneer Model 40V duplex crusher to produce coarse and fine fractions which were blended with a natural sand. Trial mixes at various asphalt contents using an 85-100 penetration asphalt cement were tested and the mix selected consisted of 39 percent coarse glass, 29.5 percent fine glass, 29.5 percent natural sand, 2 percent hydrated lime and 5 percent asphalt on a total weight basis. The gradation of the combined aggregate is shown in Table 30 and the Marshall test values for the selected mix are given in Table 31.

TABLE 30

AGGREGATE GRADATION FOR BRAMALEA GLASPHALT

	Percent Passing			
Sieve	Coarse Glass	Fine Glass	Natural Sand	Combined Gradation 39% Coarse Glass, 29.5% Fine Glass, 29.5% Sand, 2% Hydrated Lime
1/2-in.	100	100	100	100
3/8-in.	79	100	100	92
No. 4	10	90	93	60
No. 8	3	45	87	42
No. 16	1	22	75	31
No. 30	1	12	52	21
No. 50	1	7	20	10
No. 100	0	4	7	5
No. 200	0	3	4	4.1

TABLE 31

MARSHALL PROPERTIES OF BRAMALEA DESIGN MIX

Stability, lbs	800-880
Flow, .01-in.	10.4-13.0
Air Voids, %	2.2
VMA, %	13.8

A Barber-Greene 4000 lb. Batch-o-matic batch plant was used for mixing the material at 275F and the haul distance from the plant to the Bramalea project was approximately 25 miles. The paving operation used a Barber-Greene Model SA-40 paver and three rollers were used on the project: a Buffalo-Springfield KT8-4-6 ton steel-tired roller, a Galion Rollomatic 12-14 ton steel-tired roller and a Bros 7-wheeled SP-6000 rubber tired roller. The first two loads of glasphalt were breakdown-rolled with the 14-ton steel-tired roller. The mix was too tender to support this heavy roller initially and the mix had to be left to cool. The procedure was then changed to breakdown with the 5-ton steel tired roller followed by the pneumatic-tired roller. This sequence gave good results with no difficulty in rolling or pick-up.

Three samples of glasphalt were taken from the paver hopper at the job site and two samples were taken from the trucks being loaded at the asphalt plant. Marshall test and extraction results of these samples are summarized in Tables 32 and 33.

TABLE 32

MARSHALL TEST RESULTS FOR BRAMALEA FIELD SAMPLES

	Sample No.				
Marshall Properties	1	2	3	4	5
Stability, lbs	1465	1300	770	1190	1120
Flow, .01-in.	8.9	12.4	9.8	9.8	10.6
Air Voids, %	5.1	2.7	3.5	5.0	2.9
VMA, %	16.8	14.4	15.2	16.9	14.7

In September 1970, four skid tests were conducted using an ASTM skid trailer at 20 mph. The skid numbers obtained were 47, 56, 53, and 61 with an average of 54. Skid tests are normally carried out at speeds of 30 and 60 mph but these speeds could not be obtained because of the configuration of the test area. The minimum skid number for a 30 mph speed is 36 and based upon experience, as well as a study of the surface texture, it was concluded that the glasphalt skid number at the higher speeds would be higher than the minimum requirement.

TABLE 33

EXTRACTION RESULTS FOR BRAMALEA FIELD SAMPLES

Sample No.	Asphalt Content	Aggregate Grading - % Passing 3/8"	No. 4	No. 8	No. 16	No. 30	No. 50	No. 100	No. 200
1	5.2	97	79	66	55	38	18	9	5.1
2	5.1	95	66	51	42	29	16	7	3.6
3	5.1	94	66	52	40	28	14	7	3.3
4	5.0	95	70	55	44	31	15	7	3.7
5	5.1	98	82	69	58	38	18	8	4.6

On November 10, 1970, approximately 10 weeks after the paving, 2 sets of 3 cores, each 6-in. in diameter, were cut, one set from a tangent section and one set from a ramp. Results of laboratory tests on the cores are given in Table 34.

TABLE 34

RESULTS OF LABORATORY TESTS ON BRAMALEA CORES

Sample No.	Location	Percent Voids	Percent Compaction
1	Top-ramp	7.8	97.0
2	Binder-ramp	7.5	96.6
3	Top-tangent	7.9	96.1
4	Binder-tangent	9.8	93.8

Inspection of the pavement 14 months after placing revealed little raveling or loss of surface material as seen in Fig. 15. In one area, however, there were several "punching" failures consisting of rectangular depressions approximately 4 inches long, 2 inches wide, and over an inch deep as shown in Fig. 16. These were found to have been caused by large steel garbage bins which were parked filled on the pavement for a period of three months during hot weather due to a strike at the plant. The 6 cu yd capacity bins with an empty weight of 650 lbs rested on steel casters and this resulted in large concentrated loads under the casters. Other than these holes, the pavement surface was in good condition and its performance has been satisfactory.

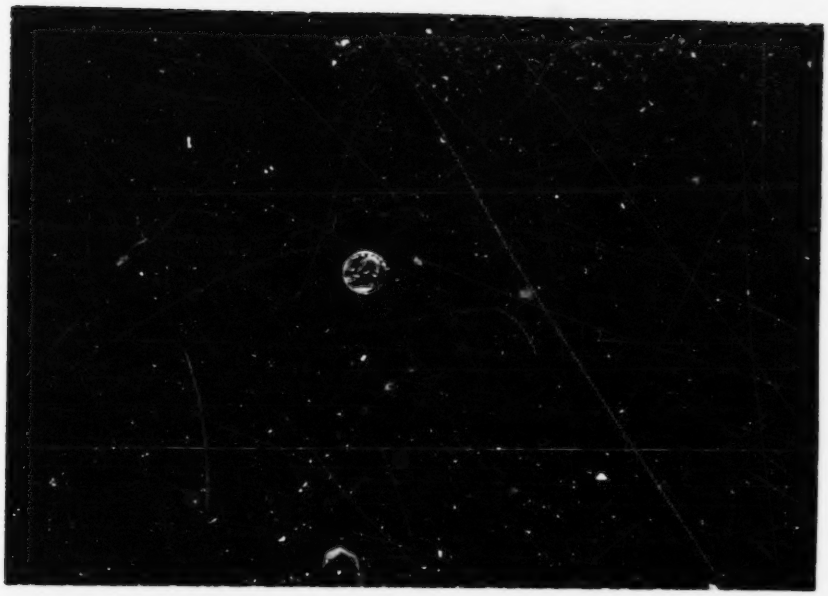

Fig. 15 Surface Texture of Bramalea Glasphalt Road after 15 Months of Service

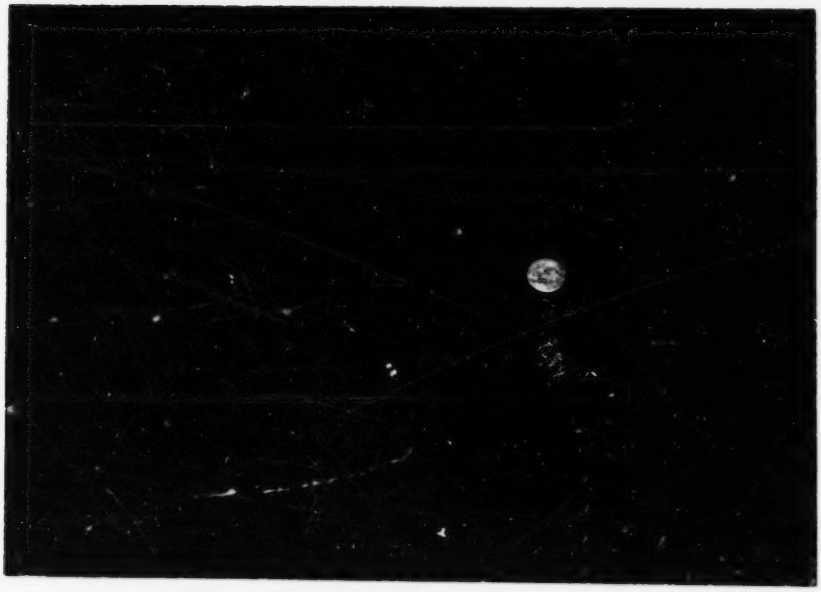

Fig. 16 Depression in Bramalea Glasphalt Road Caused by Concentrated Load

Scarborough, Ontario

Scarden Avenue, a public road in the Borough of Scarborough, Ontario, was paved with glasphalt on October 17, 1970. Approximately 600 feet of 26-foot wide pavement was placed in one course of 1-in. compacted thickness on a previously placed conventional binder course.

Design and testing of this installation was also carried out by the Ontario Department of Highways and the following data and descriptions are abstracted from the report.[16]

Materials used and the design mix were similar to those used for the Dominion Glass Company installation except that one load of the mix was modified by the addition of 2 percent asbestos and an additional 2 percent of asphalt cement to determine characteristics of asbestos-modified glasphalt. The gradation of the combined aggregate is given in Table 35 and the Marshall properties were as given in Table 31 for the Dominion Glass Company installation.

TABLE 35

AGGREGATE GRADATION FOR SCARBOROUGH GLASPHALT

	Percent Passing			
Sieve	Coarse Glass	Fine Glass	Natural Sand	Combined Gradation 39% Coarse Glass, 29.5% Fine Glass, 29.5% Sand, 2% Hydrated Lime
1/2-in.	100	100	100	100
3/8-in.	87	100	100	95
No. 4	24	95	94	67
No. 8	13	59	82	49
No. 16	8	32	70	35
No. 30	7	20	48	25
No. 50	5	12	22	14
No. 100	3	7	7	7
No. 200	2	4	5	5.5

The paving operation was performed using a Barber-Greene Model SA-35 paver and an 8-10 ton Galion steel-tired roller for breakdown with a 9-ton rubber-tired roller for finishing. No difficulties were encountered in compacting the mixture in that pushing, rutting or pick-up did not occur. However, the air temperature was 35F and the mix temperature in the paver varied from 200 to 280F.

A sample of the regular glasphalt and one of the asbestos modified mixture were taken from the paver hopper. Marshall test and extraction results are given in Tables 36 and 37.

The addition of asbestos resulted in increased flow, and a marked decrease in air voids due to the increased asphalt content but a slight decrease in stability. No cores were obtained from the compacted pavement.

TABLE 36

MARSHALL TEST RESULTS FOR SCARBOROUGH FIELD SAMPLES

Marshall Properties	Sample No. 1	2*
Stability, lbs	1090	950
Flow, .01-in.	8.9	19.7
Air Voids, %	4.4	0.6
VMA, %	16.1	16.3

*Contains 2% asbestos

TABLE 37

EXTRACTION RESULTS FROM SCARBOROUGH FIELD SAMPLES

Sample No.	Asphalt Content	Aggregate Grading, % Passing 3/8-in.	No. 4	No. 8	No. 16	No. 30	No. 50	No. 100	No. 200
1	5.1	95	69	55	45	30	12	5	2.5
2*	6.8	93	64	54	46	33	13	4	1.8

*Contains 2% asbestos

On May 3, 1971, the pavement was skid-tested using an ASTM skid trailer. At 30 mph the skid numbers ranged from 47 to 61 with an average of 55. These values are well above tentative minimum requirements and indicate good skid resistance.

Inspection of the pavement 14 months after placing revealed a considerable degree of raveling with many of the larger glass particles being dislodged from the surface as shown in Fig. 17. This may have been due to fracture of the surface particles by studded tires, although inadequate density resulting from low mix temperatures during compaction may also have contributed to the deterioration.

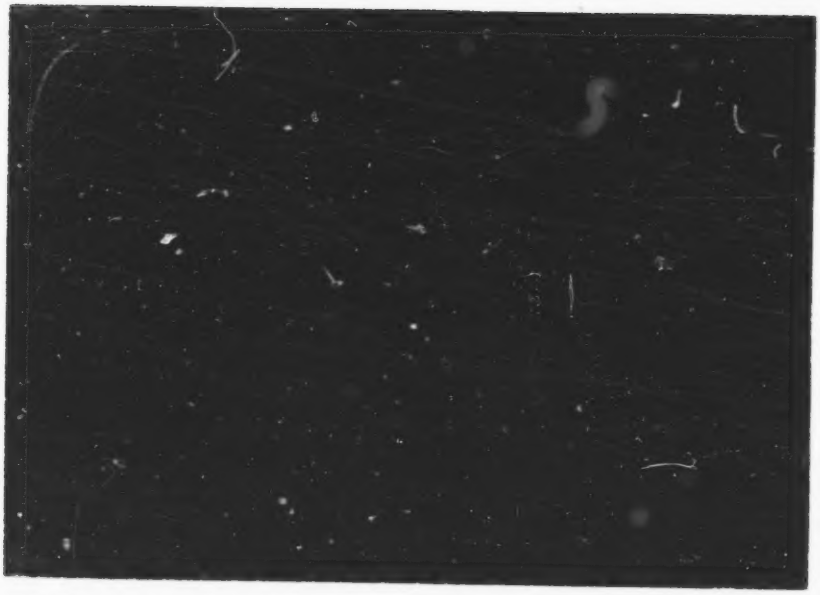

Fig. 17 Raveling of Scarborough Glasphalt Street after One Year of Service

Brockway Glass Company

Approximately 1600 square yards of roads through the employees parking lot at the Brockway Glass Company in Brockway, Pennsylvania, were paved with glasphalt on October 28, 1970. Three strips were paved with the longest being 212 feet by 24 feet wide. Thickness was 1 inch except for 156 square yards which were placed in two layers to a total depth of 5 inches. The 1-in. layer was placed as a surface course over two 2-in. layers of conventional Pennsylvania Department of Highways ID-2 binder which had been placed one week previously. The subgrade under all paving was composed of shale and ash spread over old refractory rubble and compacted through years of use.

Glass used for the project was obtained by crushing non-returnable bottles in two passes through a jaw crusher. The glass was blended with sand to produce the gradation shown in Table 38 and used for mix design studies. Marshall specimen were molded with a 60-120 penetration asphalt cement at two asphalt contents and tested with the results shown in Table 39.

TABLE 38

AGGREGATE GRADATION FOR DESIGN STUDIES
OF BROCKWAY GLASPHALT

	Percent Passing		
Sieve	Glass	Sand	Combined Gradation 46% Sand, 54% Glass
1/2-in.	100	100	100
3/8-in.	92	100	95.7
No. 4	49	100	72.4
No. 8	27	77.1	50.0
No. 16	16	47.3	30.4
No. 30	9	28.5	18.0
No. 50	5	18.2	11.1
No. 100	2	11.6	6.4
No. 200	1	8.1	4.2

TABLE 39

MARSHALL MIX DESIGN RESULTS FOR BROCKWAY GLASPHALT

	Asphalt Content	
Marshall Properties	5.0%	5.5%
Stability, lbs	1390	1400
Flow, .01-in.	10.7	10.5
Unit Weight, pcf	142.7	143.3
Air Voids, %	5.4	4.4
VMA, %	16.5	16.7

The design asphalt content was 5.0 percent (total weight basis) and the composition of the mix based upon cold feed quantities is given in Table 40. No hydrated lime was used in the mixture.

TABLE 40

GRADATION BASED ON COLD FEED FOR BROCKWAY GLASPHALT

	Percent Passing		
Sieve	Glass	Sand	Combined Gradation 46% Sand, 54% Glass
1/2-in.	100	100	100
3/8-in.	96.2	100	97.9
No. 4	52.7	100	74.4
No. 8	28.0	77.1	50.6
No. 16	16.0	47.3	30.4
No. 30	10.1	28.5	18.6
No. 50	6.9	18.2	12.1
No. 100	4.6	11.6	7.8
No. 200	3.8	8.1	5.8

Asphalt Content 5.0% (Total Weight Basis)

A Cedar Rapids spreader-finisher was used to place the material with a 10-12 ton tandem steel wheel roller and 2 ton vibratory roller being used for compaction. No difficulties were encountered in compacting the mixture. However, the unit weight of cores obtained on the day following construction was only 132.5 pcf or 92.9 percent of the laboratory compacted unit weight.

On July 8, 1971, cores were taken from the pavement for testing by the Pennsylvania Department of Transportation. Using the British Portable Tester, the cores provided skid numbers of 62, 63, 58 and 63 with 55 being generally regarded as acceptable by the Pennsylvania Department of Transportation.

An inspection of the pavement one year after placing revealed a slight amount of raveling but in general the surface was in good condition as indicated in Fig. 18. Since no hydrated lime was used in this installation, the absence of any significant stripping indicates that under some conditions the water-resistance may be adequate without the use of anti-stripping agents.

Fig. 18 Glasphalt Parking Lot in Brockway after One Year of Service

Burnaby, British Columbia

A 700 foot section of Royal Oak Avenue in Burnaby, British Columbia, was paved with glasphalt on June 18, 1971. The 20 foot wide existing asphalt pavement was tacked with a diluted emulsion before placing a 1 1/2-in. overlay. Traffic density on the road is 6000 vehicles per day (both lanes) at a maximum posted speed of 30 mph, with deceleration and acceleration occurring at the intersection with Moscrop Avenue.

The project was a cooperative effort between the Municipality of Burnaby and the Dominion Glass Company, with testing being carried out by the Department of Highways, B.C. Provincial Government.

Approximately 90 tons of bottles were crushed for use in the glasphalt and blended with conventional aggregates to produce the combined gradation given in Table 41. The combined aggregate consisted of approximately 67 percent glass, 31 percent conventional aggregate and 2 percent hydrated lime with 4.75 percent (total weight basis) of 85-100 penetration asphalt cement added to the mix.

TABLE 41

AGGREGATE GRADATION FOR BURNABY GLASPHALT

	Percent Passing			
Sieve	Glass	Albion Pit	Pipeline Pit	Combined Gradation
3/4-in.		100		100
1/2-in.	100	98.8		99.8
3/8-in.	91.3	91.0	100	92.5
No. 4	53.5	69.9	89	61.8
No. 8	31.6	55.2	76.7	42.8
No. 16	18.2	42.4	67.8	29.7
No. 30	9.9	29.1	43.8	19.4
No. 50	5.5	15.0	23.0	11.2
No. 100	3.0	6.1	10.1	6.3
No. 200	1.5	2.8	4.7	4.1

Results of Marshall tests on laboratory mixed samples and plant samples are given in Table 42. The stability and flow values are low while air voids are high.

The glasphalt was delivered to the job site at temperatures between 270 and 290F. Breakdown rolling was carried out at 230 to 270F with an 8-ton tandem roller, and subsequent rolling was done with a 7-ton pneumatic roller at temperatures from 180 to 230F. The mix was tender and required a cooling period before rolling.

TABLE 42

MARSHALL PROPERTIES OF BURNABY DESIGN MIX

Marshall Properties	Plant Samples	Laboratory-Mixed Samples
Stability, lbs	540	580
Flow, .01-in.	6.6	6.5
Unit Weight, pcf	140.3	140.0
Air Voids, %	5.7	6.0
VMA, %	15.9	16.1

Seven cores were cut from the compacted pavement and the density ranged from 96.4 to 98.5 percent of the laboratory density with an average density of 97.0 percent.

On September 16, 1971, skid tests were conducted on the glasphalt pavement as well as a conventional asphalt pavement placed during the same time period. The British Portable Tester results are given in Table 43. Note that in all cases the conventional asphaltic concrete yielded higher skid numbers than the glasphalt.

Inspection of the pavement on March 30, 1972, indicated that severe raveling had occurred in the wheel paths as shown in Fig. 19. Loose, uncoated glass particles were prevalent along the shoulder and the surface pitting shown in Fig. 20 was extensive. One pot hole, Fig. 21, had developed. This deterioration was attributed primarily to heavy studded-tire traffic resulting from an abnormally severe winter. However, low pavement density and insufficient asphalt content may also have contributed to the condition.

On May 23, 1972, additional skid tests were conducted on the glasphalt and conventional asphalt pavements. Results of these tests are shown in Table 43 and they show a substantial increase in skid resistance for the glasphalt over the values measured in September. This was probably due in part to the raveling which was previously mentioned. The glasphalt had higher average skid numbers for these measurements than the conventional asphalt pavement.

Fig. 19 Raveling of Glasphalt Road in Burnaby after One Winter

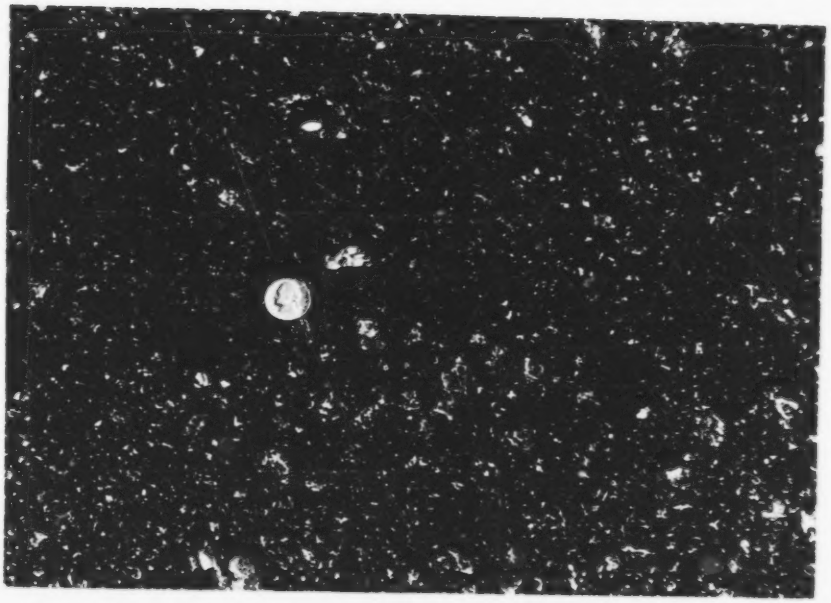

Fig. 20 Surface Pitting of Burnaby Glasphalt Road Caused by Loss of Glass Particles

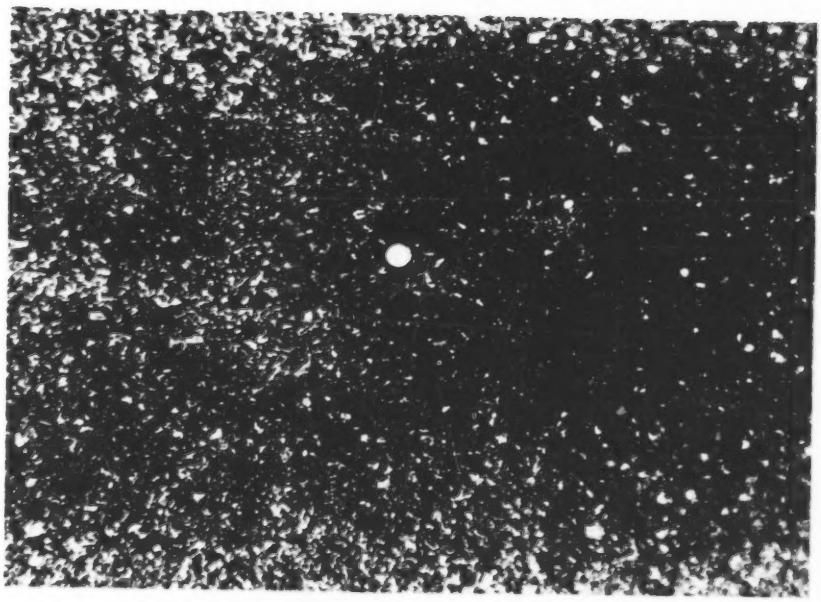

Fig. 21 Pot-Hole in Burnaby Glasphalt Road after Nine Months of Service

TABLE 43

RESULTS OF BURNABY SKID TESTS

Date	Location	British Pendulum Number		
		Glasphalt Pavement		Asphalt Pavement
		Range	Average	Average
Sept. 1971	Outer Wheel Path	45.7-52.1	49.4	57.7
Sept. 1971	Between Wheel Paths	48.7-56.5	53.3	64.2
Sept. 1971	Inner Wheel Path	45.4-54.5	48.5	54.3
May 1972	Outer Wheel Path	55.7-70.3	64.0	56.4
May 1972	Between Wheel Paths	54.0-66.0	59.3	60.5
May 1972	Inner Wheel Path	55.0-68.2	64.1	58.4

Omaha, Nebraska

One block of a city street in Omaha, Nebraska, was paved with a 1-in. glasphalt overlay on August 6, 1971. The roadway width paved was 60 feet and the length was approximately 280 feet.

Glass for the project was gathered during a bottle collection drive and crushed at a local gravel pit. Considerable difficulty was encountered in crushing the bottles. They were crushed in a Pioneer Three Roll Crusher normally used for crushing gravel with a maximum size of one inch. Several times, broken bottles became wedged in the opening to the crusher and severely cut the rubber input feed belts. Bits of glass flew from the crusher and were a definite safety hazard, resulting in several workers receiving cuts. Due to this, the time required for crushing the glass was much longer than the contractor had estimated and the cost was extremely high.

The crushed glass was blended with crushed gravel, blow sand and 3/8-in. limestone screenings to produce the combined gradation shown in Table 44. Marshall properties of specimens made at three different asphalt contents are shown in Table 45.

Properties of the mix as produced are shown in Tables 46 and 47. The design asphalt content was 6.25 percent (total weight basis) and no hydrated lime was used to control stripping.

Paving operations using conventional equipment proceeded smoothly and performance of the mat has been satisfactory. During the winter months, larger glass particles at the pavement surface were broken by studded tires and whipped out by traffic leaving numerous pock marks. Otherwise, there have been no indications of poor performance.

TABLE 44

AGGREGATE GRADATION FOR DESIGN STUDIES OF OMAHA GLASPHALT

Sieve	Percent Passing				
	Crushed Gravel	Crushed Glass	Blow Sand	3/8-in. Limestone Screenings	Combined Gradation 30% Gravel, 20% Glass, 10% Sand, 40% Limestone
3/8-in.	100	100		100	100
No. 4	94	78		85	87.8
No. 8	59	46		55	58.9
No. 16	36	29		36	41.0
No. 30	24	18	100	25	30.8
No. 50	15	11	94	19	23.7
No. 100	9	6	20	15	11.9
No. 200	5	3	3	12	7.2

TABLE 45

MARSHALL MIX DESIGN RESULTS FOR OMAHA GLASPHALT

Marshall Properties	Asphalt Content (TWB), % 5.50	6.25	7.00
Stability, lbs	1600	1810	1780
Flow, .01-in.	9	11	13
Unit Weight, pcf	142.2	144.8	145.4
Air Voids, %	5.8	3.3	2.1
VMA, %	18.2	17.7	18.2

TABLE 46

GRADATION OF OMAHA GLASPHALT AS PRODUCED

Sieve	Percent Passing Calculated (Cold Feed)	Extraction
3/8-in.	100	100
No. 4	88.6	86.6
No. 8	60.9	58.5
No. 16	43.2	40.7
No. 30	33.4	29.7
No. 50	23.9	22.4
No. 100	11.5	10.7
No. 200	8.0	6.1

Asphalt Content by extraction 6.19% (TWB)

TABLE 47

MARSHALL PROPERTIES OF PLANT SAMPLES FOR OMAHA GLASPHALT

Stability, lbs	2170
Flow, .01-in.	10
Unit Weight, pcf	145.4
Air Voids, %	2.9

EVALUATION OF GLASS-ASPHALT PAVEMENT PERFORMANCE

Skid Resistance

The skid resistance measured on several of the glasphalt pavements described has, with one exception, been adequate after periods of service up to two years in duration.

A British Portable Tester was used to measure skid resistance on the Rolla, Brockway and Burnaby installations. After two years of service, the average British Pendulum Number (BPN) for the Rolla Street was 49.5 for the coarse mixture and 52.0 for the fine mixture. Natural rubber sliders were used for these measurements rather than ASTM E249 synthetic rubber sliders. Tests conducted by Kummer and Moore[17] show that the synthetic rubber sliders give BPN values that are 10 to 15 percent higher than numbers obtained with natural rubber sliders. In "Tentative Skid-Resistance Requirements for Main Rural Highways"[18], Kummer and Meyer list tentative minimum skid resistance requirements for various testing methods and test speeds. These requirements for the British Portable Tester are given in Table 48. A 10 percent correction for use with data obtained with natural rubber sliders has been applied to these figures and is shown in the table. Based upon these corrected figures, the minimum recommended BPN for both coarse and fine mixtures is above this minimum value.

TABLE 48

RECOMMENDED MINIMUM SKID RESISTANCE REQUIREMENTS

Mean Traffic Speed (mph)	Skid Number		British Pendulum No.	
	SN*	SN_{40}+	BPN_{SR}±	BPN_{NR}¢
0	60	--	--	--
10	50	--	--	--
20	40	--	--	--
30	36	31	50	45
40	33	33	55	50
50	32	37	60	55
60	31	41	65	59

*Measured at mean traffic speed
+Measured at 40 mph
±Measured in accordance with ASTM E 303 using ASTM E 249 rubber
¢Corrected for use of natural rubber sliders as suggested by Kummer and Moore

The average BPN for cores from the Brockway parking lot was 61.5, which is well above the recommended minimum value of 50 for 30 mph speed using ASTM E249 sliders.

The average BPN measured in the wheel paths of the Burnaby glasphalt road after 3 months of service was 48.9 which is slightly below the recommended minimum value of 50. The BPN had risen to 64.0 after 11 months of service, but raveling probably caused much of this increase. Measurements were also made on an adjacent conventional asphalt pavement which had been placed at the same time and the average values obtained in the wheel paths were 56.0 and 57.4 after 3 and 11 months respectively.

The Fullerton, Bramalea, and Scarborough roads were tested using the ASTM towed trailer (ASTM E274). The Fullerton tests were conducted at 25 mph and yielded skid numbers (SN) ranging from 61 to 69. These values, converted to 40 mph were 54 and 62 respectively, which are well above minimum requirements shown in Table 48.

Tests on the Bramalea road, conducted at 20 mph, yielded SN values ranging from 47 to 61 with an average of 54. Skid test results on the Scarborough street tested at 30 mph ranged from SN47 to SN61 with an average of SN55. These values are also well above minimum requirements shown in Table 48.

The results of these skid tests show that pavements containing glass aggregates have generally maintained adequate skid resistance levels under the service conditions described and for the time periods indicated.

Only limited data were available from the Burnaby installation to permit a comparison of the skid resistance of glasphalt and conventional asphaltic concrete. However, additional data were obtained from a series of test patches with varying composition which were placed in a Rolla city street. Five different combinations of aggregate were used in the test patches. One mixture contained an all-glass aggregate with particles ranging in size from 1/2-in. through minus 200 mesh material. Two mixtures contained crushed limestone in the coarse sizes (1/2-in. to plus No. 8 material) with river sand fines in one mixture and glass fines in the other. The other two mixtures consisted of river gravel in the coarse sizes, with river sand fines in one mixture and glass fines in the other.

Since specific gravities for the different aggregates varied from 2.50 to 2.57, the weight of aggregate was adjusted so that the volume of aggregate in each size fraction remained the same regardless of the aggregate composition. The gradation used, based on volume, is given in Table 49.

Each mixture was designed with an effective asphalt content of approximately 5.5 percent (total weight basis) and all mixtures contained one percent hydrated lime by weight of the aggregate. Results of laboratory Marshall tests on the mixtures are given in Table 50.

TABLE 49

GRADATION OF AGGREGATES USED IN PATCHES FOR SKID RESISTANCE TESTS

Sieve	Percent Passing (by Vol.)
1/2-in.	100
3/8-in.	87
No. 4	69
No. 8	50
No. 16	38
No. 30	28
No. 50	22
No. 100	11
No. 200	3

TABLE 50

MARSHALL PROPERTIES OF LABORATORY SPECIMENS FOR SKID RESISTANCE PATCHES

Mix Type	Effective Asphalt Content	Unit Weight (pcf)	Air Voids (%)	VMA (%)	Stability (lbs)	Flow (.01-in.)
All Glass	5.50	138.8	3.64	15.72	515	9
Stone-Glass	5.40	140.4	3.63	15.71	760	10.5
Gravel-Sand	5.50	140.0	2.91	15.15	1230	9
Gravel-Glass	5.60	136.7	4.06	16.12	750	8
Stone-Sand	5.40	143.4	2.70	14.91	1275	10

Two lines of five 12 by 18 inch patches were placed in one lane of the road and each line of patches contained all five of the different mixtures. A vibrating plate compactor was used to compact the patches. Results of tests on laboratory compacted field samples from each of the mixtures are given in Table 51.

Skid resistance of these patches was measured periodically over a 23 month period with the British Portable Tester. Eight individual measurements were made on each patch each time the skid resistance was evaluated, from which an average BPN was calculated. The variation in BPN with time for each mixture is shown in Figure 22.

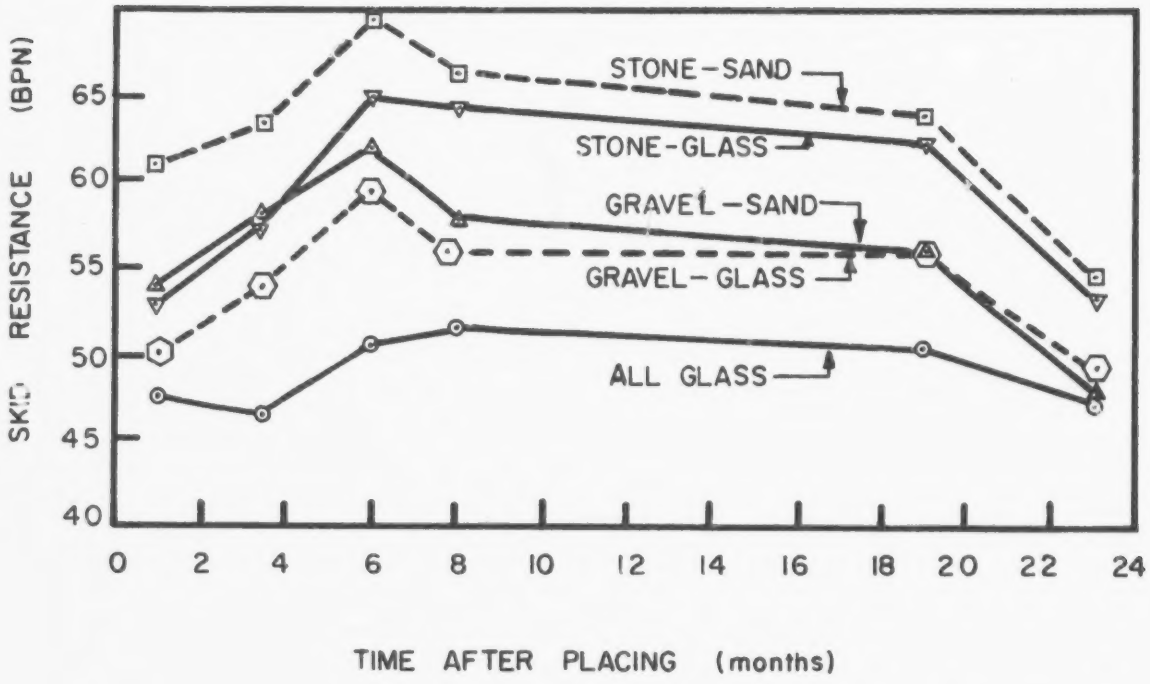

Fig. 22 Variations in Skid Resistance with Time for Asphaltic Concrete Patches Containing Different Aggregates

TABLE 51

MARSHALL PROPERTIES OF LABORATORY COMPACTED FIELD SAMPLES FROM SKID RESISTANCE PATCHES

Mix Type	Effective Asphalt Content	Unit Weight (pcf)	Voids (%)	VMA (%)	Stability (lbs)	Flow (.01-in.)
All Glass	5.40	138.1	4.43	16.24	350	7.3
Stone-Glass	5.50	138.3	4.96	16.33	510	10.3
Gravel-Sand	5.50	137.5	3.45	15.59	1360	11.3
Gravel-Glass	5.60	135.8	4.63	16.61	1095	9.7
Stone-Sand	5.50	143.4	2.49	15.01	1650	9.3

Data obtained after 23 months are shown in Table 52. Comparisons between the average British Pendulum Numbers for the various treatments were made using a t-test and only two significant differences between treatment means were indicated at a 0.05 significance level. The average BPN for the all-glass mixture was significantly lower than the BPN for the stone-sand mixture and the stone-glass mixture. However, there was no significant difference between the stone-sand and the stone-glass mixtures or the gravel-sand and gravel-glass mixtures. Nor was there a significant difference between the all-glass mixture and the gravel-glass or gravel-sand mixture. This indicates that a replacement of stone by coarse glass lowered the skid resistance, but the replacement of gravel by coarse glass has no effect upon skid resistance. The replacement of river sand by fine glass resulted in no significant change in skid resistance for mixtures with either gravel or stone coarse aggregate.

TABLE 52

SKID RESISTANCE OF FIELD PATCHES AFTER 23 MONTHS OF SERVICE

Mix Type	British Pendulum Number (BPN)	
	Average	Range
All Glass	47.4	43.8 - 51.4
Stone-Glass	53.3	47.5 - 61.2
Gravel-Sand	47.8	44.3 - 52.5
Gravel-Glass	48.5	43.1 - 55.5
Stone-Sand	54.6	47.2 - 62.7

Since the measured skid resistance was lower during the summer months, and differences among the skid numbers of the various mixtures were not as pronounced, a similar analysis was conducted using the British Pendulum Numbers obtained after 19 months and shown in Table 53. The results of this

analysis indicate several significant differences among the mixtures. The average BPN for the all-glass mixture was significantly lower than the BPN for either stone-sand or gravel-sand mixtures. Stone-glass and gravel-glass mixtures also had higher average BPN's than the all-glass mixture. There was again no significant difference between the stone-sand and stone-glass mixtures or the gravel-sand and gravel-glass mixtures. This indicates that the replacement of either gravel or stone by coarse glass lowered the skid resistance while replacement of fine sand by fine glass has no effect upon skid resistance.

TABLE 53

SKID RESISTANCE OF FIELD
PATCHES AFTER 19 MONTHS OF SERVICE

Mix Type	British Pendulum Number (BPN)	
	Average	Range
All Glass	50.4	46.4 - 58.6
Stone-Glass	62.7	60.0 - 65.6
Gravel-Sand	56.1	51.6 - 62.4
Gravel-Glass	56.1	50.4 - 58.6
Stone-Sand	64.1	58.4 - 69.4

Based upon the above analyses, the replacement of river sand by fine glass results in no significant change in skid resistance. Substitution of coarse glass for crushed stone reduces the skid resistance, but the effect of substituting coarse glass for gravel is inconclusive. After 19 months of service the results indicated that the glass for gravel replacement lowered the skid resistance, while results obtained after 23 months showed no difference in the skid resistance.

Aggregate Degradation

There was no indication of excessive aggregate degradation based upon sieve analyses of pavement samples taken from the Rolla and Fullerton glasphalt roads. A comparison of plant samples and samples sawed from the Rolla pavement after two years of service shows an increase in Hudson's $\bar{A}$ of 0.15 and 0.17 for the coarse and fine mixtures respectively. Hudson's $\bar{A}$ increased from 4.58 for the plant sample taken at Fullerton to 4.87 for cores obtained after one year of service giving a total increase of 0.29. Thus, the effect of field compaction and subsequent traffic on the aggregate gradation was minimal.

Surface Deterioration

Raveling has been a problem in two of the glasphalt installations. The Burnaby road exhibited the greatest degree of deterioration. Pronounced raveling was noted in the wheel paths after the first winter. Glass aggregates which had been dislodged from the pavement had no asphalt remaining on the surface. A similar, though not as sever, deterioration had occurred on the Scarborough street after a year of service. The material lost from the surface in this case was primarily coarse glass particles which had fractured and then been dislodged by further traffic. The deterioration in both of these cases was probably initiated by studded tire traffic with subsequent asphalt stripping from the loose particles.

Raveling in the Fullerton, Brockway and Omaha pavements was less severe and was confined primarily to the loss of large particles at the surface. Little raveling had occurred on the Rolla and Bramalea pavements.

In a laboratory study of raveling characteristics of hot mix asphalt paving mixtures, Gallaway and Vavra[19] found that increasing voids in the pavement (lower densities) resulted in increased raveling. In their studies, raveling was not found to be significant except where the void content was 10 percent and higher for specimens made with good aggregates. Specimens made with poor aggregates showed significant raveling at all void contents, but the raveling definitely increased with increasing void content. Based upon field density tests of the Burnaby glasphalt, the void content of the compacted pavement was 8.67 percent. Since this is below the 10 percent figure suggested by Gallaway and Vavra, it is unlikely that inadequate density alone accounts for the raveling which occurred, although it may have contributed to the severity of the problem.

No cores were taken from the Scarborough pavement and thus the void content of the compacted pavement could not be computed. However, due to the low ambient temperatures during construction, it is possible that a high void content in the pavement may have been a contributing factor in the raveling observed.

The void content of the compacted pavements at Fullerton and Brockway was higher than 10 percent, but the lower traffic volumes at these sites may explain the fact that extensive raveling has not occurred.

There was little deterioration of other types occurring in the glasphalt pavements described. One pot hole had developed in the Burnaby road and alligator cracking was found in one small area of the Rolla road. Punching failures due

to sustained concentrated loads during hot weather occurred in the Bramalea road, but there was no rutting or other evidence of low stability in any of the other pavements containing glass aggregates.

EFFECTS OF GLASS AGGREGATES UPON ABRASIVENESS OF ASPHALTIC MIXTURES

Development of Equipment

In order to determine the effects of glass aggregates upon tire wear, a laboratory testing apparatus was developed to determine the relative abrasiveness of compacted paving mixtures containing varying combinations of glass and conventional aggregates. The apparatus consisted of a rubber wheel of standard composition which was rotated while in contact with the surface of a small sample of the compacted paving mixture. Weight loss for the wheel was measured and used as an indication of the abrasiveness of the surface.

The design of the equipment was suggested by the B. F. Goodrich Company[20] and Fig. 23 shows the apparatus as built. The test wheel was 4-in. in diameter, 1/2-in. wide and was prepared from the standard ASTM E-17 skid compound. It was mounted on an axle rotated by a 3/8-in. electric drill with a gearing assembly and speed control to provide speeds in the range of 50 to 250 rpm.

The drill and wheel assembly was mounted on a plate attached to a vertical shaft passing through two sleeve bearings and counterweighted to minimize eccentricity of loading. Additional weights could be placed on the shaft to vary contact pressure.

The asphalt specimen was placed on a movable platform to permit lateral adjustment so that the wheel could be placed at any position on the specimen surface.

Fabrication of Specimens

Two sets of sixteen specimens each were molded in the laboratory to measure abrasiveness of mixtures containing different aggregate types. Gradation on a volume basis for aggregates used in all specimens was identical to the gradation used in patches for skid resistance studies (Table 48). Since the aggregates used had different specific gravities, weights were adjusted to keep the gradation by volume constant.

One set of specimens contained four different coarse aggregates (plus No. 8 material): glass, traprock limestone and river gravel. The fine aggregate for these specimens was crushed container glass with one percent hydrated lime by weight of the aggregate. Aggregates were sieved into nine size fractions which were combined to produce the desired gradation. The asphalt content for all specimens was 5.5 percent (total weight basis) and four specimens containing each of the four coarse aggregates were made.

a	Rubber Wheel	f	Counter-weights
b	3/8" electric drill	g & h	Sleeve bearings
c	Shaft & ball bearing assembly	i	Weights for load variation
d	Test specimen	j	Shaft
e	Wooden platform	k	Bearings for lateral movement

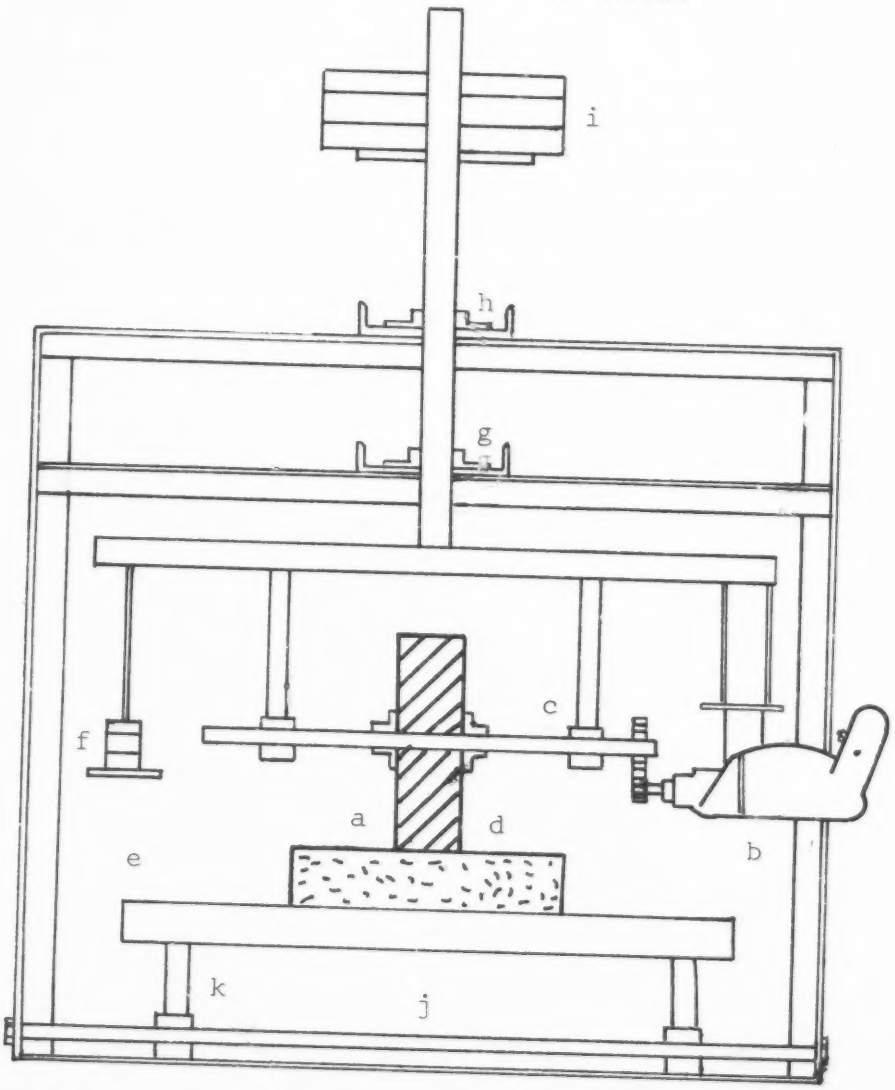

Fig. 23 Schematic Diagram of Laboratory Wheel Abrasion Testing Apparatus

Procedures for preparation of the mixtures were in accordance with ASTM D1559. A standard Marshall compaction hammer was modified by adding a rectangular compaction plate 3 1/2-in. wide and 6-in. long and each specimen was compacted with 100 blows on one side only. The compacted specimens were 6-in. long, 3 1/2-in. wide and approximately 1 1/2-in. thick.

The second set of specimens contained four different fine aggregates (minus No. 8 material): glass, traprock sand, limestone sand, and river sand. The coarse aggregate for these specimens was limestone. In order to determine the angularity of the fine aggregates used, a procedure described by Rose and Havens [21] was utilized. Fine aggregate samples consisting of different size fractions were dropped into a mold of known volume from a funnel at a fixed height above the mold. After striking off the surface weight of aggregate in the mold was determined and percent voids was calculated using the specific gravity of the aggregate. The average percent voids for size fractions from minus No. 8 to plus No. 50 material is shown in Table 54.

TABLE 54

ANGULARITY OF FINE AGGREGATES
USED IN WEAR STUDIES

Aggregate	Angularity No. (No. 16, 30 & 50 sieves) (%)
Glass	52.6
River Sand	46.6
Limestone Sand	52.9
Traprock Sand	56.4

The asphalt content for all specimens was again 5.5 percent and 1 percent hydrated lime by weight of the aggregate was added to each specimen.

Procedures for preparation and compaction of the specimens were identical to those used for the coarse aggregate specimens. Four specimens containing each of the four different fine aggregates were made.

In order to assess the abrasiveness of asphaltic mixtures which had been subjected to traffic and weathering, specimens were cut from the field patches which had been placed for use in studying the skid resistance of mixtures containing glass and conventional aggregates. These were described in the previous section. Samples were sawed from patches containing five different combinations of glass and conventional aggregates which had been subjected to traffic for 23 months.

Testing Procedures

Ten locations on the specimen surface were chosen by superimposing a numbered grid on the surface and randomly choosing ten numbers corresponding to ten different locations.

The test wheel was weighed and mounted in the apparatus, placed on the first location, then rotated for three minutes at 100 rpm while in contact with the surface. It was then moved within thirty seconds to a new location and rotated for three minutes at 100 rpm. This procedures was repeated at each of the remaining locations with a thirty second interval in which to position the wheel, after which the wheel was removed from the apparatus and weighed to determine weight loss.

A test was conducted on both sides of each laboratory compacted specimen and a different wheel was used for each of the four mixtures containing different aggregates which were made on the same day. Thus, there were four replications requiring four wheels for each the coarse and fine series testing.

In testing the samples cut from patches which had been in service for two years, six specimens were cut from each of the five patches. Three different wheels were used and each wheel was used on two specimens.

During testing, as the temperature of the wheel increased, the specimen surface was severely abraded by the wheel. An attempt was made to decrease this abrasion by inserting a spring between the top sleeve bearing and the loading platform. This reduced the contact pressure on the wheel from 55 to 31 psi. However, in tests conducted at this loading, wheel weight losses were extremely small, making it difficult to draw conclusions about differences in specimen composition. A further attempt to decrease the abrasion was made by increasing the number of locations on the test specimen from 10 to 15 and decreasing the test period from 3 to 2 minutes per location. This procedure, however, still produced surface abrasion. Consequently, it was decided to conduct the tests at 10 locations with a three minute duration at each location.

Test Results

Wheel weight losses measured in the three sets of tests conducted are shown in Tables 55 through 57. An analysis of variance procedure was used to compare mean weight losses produced by the varying aggregate combinations. Where significant difference among the means was indicated, single degree of freedom comparisons were made to compare mixtures containing glass aggregates with conventional aggregate mixtures.

TABLE 55

WHEEL WEIGHT LOSSES ON
ASPHALTIC MIXTURES WITH VARIOUS
COARSE AGGREGATES

Replications		Weight Loss (g.)			
		Glass	Traprock	Limestone	Gravel
1	Top	1.9	1.1	1.0	1.4
	Bottom	1.7	1.1	0.8	1.0
2	Top	1.8	2.15	1.30	1.2
	Bottom	1.4	1.80	1.50	1.3
3	Top	1.35	1.65	0.95	1.1
	Bottom	1.70	1.00	1.10	1.3
4	Top	2.4	1.4	1.1	1.5
	Bottom	1.2	1.2	1.0	1.0
Mean Weight Loss		1.70	1.45	1.10	1.25

TABLE 56

WHEEL WEIGHT LOSSES ON
ASPHALTIC MIXTURES WITH VARIOUS
FINE AGGREGATES

Replications		Weight Loss (g.)			
		Glass	Traprock	Limestone	Sand
1	Top	0.8	0.6	0.4	0.8
	Bottom	0.6	0.8	0.6	0.6
2	Top	1.2	0.6	0.6	1.1
	Bottom	0.4	0.2	0.6	0.8
3	Top	1.3	0.8	0.9	0.9
	Bottom	0.8	0.3	0.4	1.1
4	Top	1.2	0.6	0.8	0.7
	Bottom	0.9	0.2	0.6	1.0
Mean Weight Loss		0.9	0.5	0.6	0.9

TABLE 57
WHEEL WEIGHT LOSSES ON
FIELD PATCHES WITH
VARIOUS AGGREGATES

Replications		Weight Loss (g.)				
		All-Glass	Limestone-Glass	Gravel-Sand	Gravel-Glass	Limestone-Sand
1	First	1.7	0.8	0.5	1.3	0.4
	Second	2.5	0.8	0.9	2.0	0.8
2	First	2.0	0.6	0.6	1.6	0.6
	Second	1.3	0.9	1.1	1.1	0.4
3	First	2.8	1.0	0.6	1.7	0.4
	Second	1.6	0.9	0.6	1.4	0.6
Mean Weight Loss		2.0	0.85	0.70	1.50	0.55

In the set of specimens containing different coarse aggregates, a statistically significant difference among means was indicated at a 0.05 significance level. The mean wheel weight loss for tests on mixtures containing coarse glass was greater than that for mixtures containing either limestone or gravel coarse aggregates, but was not significantly different from the weight loss produced by mixtures containing traprock.

For specimens containing different fine aggregates, a statistically significant difference among means was also indicated at a 0.05 significance level. The mean wheel weight loss for tests on mixtures containing glass fines was greater than that for mixtures containing either limestone or traprock fine aggregates, but was not significantly different from the weight loss produced by mixtures containing river sand.

Results of wear testing on the field samples were in agreement with the tests on laboratory compacted specimens when mixtures containing coarse glass aggregates were compared with mixtures containing conventional coarse aggregates. The mean weight loss resulting from tests on all-glass mixtures was significantly higher than weight losses measured for gravel-glass and limestone-glass mixtures. Comparison of weight losses between limestone-glass and limestone-sand mixtures also confirmed the finding that no significant different in wear resulted from the substitution of fine glass for river sand. However, a significant difference in

weight loss was found when comparing gravel-sand and gravel-glass mixtures. The gravel-glass mixture produced higher weight losses than were found with gravel-sand mixtures.

It is interesting to compare these results with the results of studies by Lowne[22] on the effects of road surface texture on tire wear. His data indicate that wet coefficient of friction and a factor related to the density and shape of asperity tips can be used to predict tire wear ratings for differing surfaces, with higher coefficients of friction and greater density and sharpness of the asperity tips resulting in higher wear. Macro-texture, indicated by surface roughness which can be seen by eye, was found to be only a slightly modifying factor in tire wear.

In our studies, the coefficient of wet friction was measured with a British Portable Tester on the field patches immediately before they were tested in the laboratory wear apparatus. The average wear corresponding to differing coefficients of friction is shown in Table 58. There is a trend toward decreasing weight loss with increasing skid resistance, whereas Lowne's study indicates that the reverse should be true. Furthermore, the data from tests on laboratory compacted specimens with differing fine aggregates show a trend toward decreasing wear or wheel weight loss with increasing angularity, while Lowne's data suggests that sharper asperity tips should increase wear. Since the surface specimens tested in the laboratory wear test was severely abraded by the spinning wheel, the effect of initial coefficient of friction was minimized. Abrasion would also be expected to continuously expose new particle tips so that polishing of the surface which might take place under traffic conditions would not occur in the laboratory test. Consequently, the laboratory testing method may not accurately reflect differences in tire wear resulting from surfaces of varying composition.

TABLE 58

WHEEL WEIGHT LOSSES FOR SURFACES
WITH VARYING COEFFICIENT OF FRICTION

Mixture	Wet Coefficient of Friction	Av. Wt. Loss (g.)
All glass	0.485	2.0
Limestone-glass	0.528	0.85
Limestone-sand	0.561	0.55
Gravel-glass	0.503	1.50
Gravel-sand	0.483	0.70

ECONOMIC ANALYSIS

The economic feasibility of using waste glass as an aggregate is dependent upon several factors which include the cost of disposing of waste by conventional methods of disposal such as sanitary landfilling or incineration, the cost of separating refuse into recyclable components and the cost of conventional aggregates.

Costs of Conventional Disposal Methods

Cost ranges for sanitary landfill disposal have been estimated at $0.50 to $2.00 per ton by Cannela[23] and more recently at $1.50 to $3.00 per ton.[24] Incineration costs are generally somewhat higher with an average operating cost of $5.00 per ton being reported by DeMarco et al[25] on the basis of results from a 1968 National Survey of Community Solid Waste Practices. Based upon data from 78 facilities at which incoming refuse was actually weighed, 73 percent of the incinerators studied had operating costs below $5.00 per ton while four of the 78 plants reported operating costs above $10.00 per ton.[25]

Costs of Refuse Separation Facilities

Costs of separating refuse for the purpose of recycling the separated components vary with the methods used for separation. Non-profit organizations and community action groups have set up recycling centers throughout the United States using volunteer labor, and industry groups such as glass container and can manufacturers have also established reclamation centers. Materials such as paper, glass containers and metal cans are collected for recycling and, in some cases, donors are paid for material brought to the center. Up to $20 per ton has been paid for reasonably clean glass containers. The volume of material collected in this manner, however, is relatively small. In Los Angeles, for instance, 130,000 tons per year of residential materials are salvaged, but 4.20 million tons of solid wastes are landfilled.[26]

If recycling is to be practiced on a large scale, automated systems for segregating and recovering portions of residential solid waste will be necessary. Several such resource recovery systems are currently being developed by the U. S. Bureau of Mines[27], Black Clawson Company[28], Combustion Power Company and Garrett Research. These include both dry and wet separation systems for treating either incinerator residue or raw refuse. Processing steps that have been utilized include crushing, screening, air classification, heavy media separation, and magnetic separation. Detailed data on

the capital and operating costs for these systems is scarce, however. Costs of treatment for the Black Clawson system have been reported to be an estimated $7.50 per ton of raw refuse processed [29] minus the credits for salable separated components. Sullivan and Stanczyk[30] give cost data on the Bureau of Mines system which treats incinerator residue.

The most comprehensive analysis of the costs for separating refuse is given in an engineering feasibility study for a materials recovery system which is being developed by the National Center for Resource Recovery, Inc.[31] Their plan calls for a facility which would process 500 tons of refuse per day and would incorporate "off-the-shelf" equipment used in other process industries. Major separation equipment items would include a shredder, air classifier, magnetic belt separator, roll crusher, electrostatic separator and optical separator along with the required hoppers, conveyors and other processing equipment.

Recovered material from the system is predicted to be 15 to 20 percent of the input by weight, with the remainder being disposed of by conventional methods. Since the value of recovered products does not cover the cost of extracting them from the refuse, economic viability of the system requires benefits as a result of shredding -- either lowering the cost of landfill due to less cover requirements or increasing the efficiency of an incinerator. Also, there are savings incurred by simply not having to dispose of the recovered materials.

A cost analysis for the system details estimated capital requirements of $2,416,000 which includes $100,000 working capital. Under the conditions outlined in the report, annual revenues from sale of materials and collection of dumping and processing fees would approximate $1,030,000 while annual net expenses would be $818,000. Thus, an expected profit of $212,000 per year would yield a return on equity of 14.6 percent for a debt-equity ratio of 40-60. Several assumed conditions, especially those relating to the glass fraction, are of interest.

The facility was targeted for a city that has a disposal cost of $6.50 per ton or higher. Thus the facility charges the city $6.50 for every ton of solid waste that is delivered and therefore does not have to be disposed of by traditional means. A $2.00 per ton processing charge is assumed for shredding and removing the inerts from the unrecovered refuse.

Estimated revenues generated by the recoverable glass fraction are dependent upon whether color sorting is employed. Glass is assumed to comprise 10 percent by weight of the raw feed input to the system or 50 tons per day. Of this 50 tons, 32 tons are expected to be recovered while the remainder

is landfilled. Twenty of the 32 tons recovered may be color sorted and are assumed to have a market value of $12 per ton after color sorting while the remaining 12 tons consists of material smaller than a 3/16 in. screen but retained on a 20 mesh screen and suitable for aggregate with a market value of $1 per ton. Since color sorting equipment is optional, however, one portion of the economic analysis assumes that no color sorting is carried out and all recovered glass has a market value of $1 per ton. This lowers the return on equity from the previously stated 14.6 percent to 10.2 percent.

Costs of Conventional Aggregates

Costs of conventional aggregates generally range from $1.00 to $7.00 per ton depending upon the locality and type of aggregate. Monthly market quotations reported by Engineering News Record[32] for January 1973, give sand prices ranging from $1.00 per ton in Detroit to $5.40 per ton in Pittsburgh. The price of 3/4-in. gravel in Birmingham was $1.65 per ton while in New Orleans the price was $7.00 per ton. Crushed stone with a 3/4-in. maximum size had a price range from $1.55 per ton in St. Louis to $6.50 per ton in Minneapolis. The average aggregate prices per ton in the twenty U.S. cities surveyed were $3.17, $3.79, and $3.55 for sand, gravel and crushed stone respectively.

The variations in aggregate prices for different cities reflect the availability of aggregates in these areas. The Gulf Coast in Texas, Louisiana, Alabama and portions of Florida is an area in which quality aggregates are lacking and consequently the prices are higher in this area. A study by the American Road Builders' Association was used in NCHRP Report No. 135[33] to estimate the yearly tonnage of aggregates needed in various regions of the United States through 1985. The results of this study indicated that the aggregate demands for highways in the Northwestern United States will not be met in the future unless:

1. Aggregate production increases in excess of 5 percent per year are encountered,

2. The amount of aggregate for highway consumption expressed as a percentage of total aggregate production for the region is greatly increased over 40 percent,

3. Conventional aggregate is transported into the region from other regions,

4. Supplemental aggregates are manufactured and used for highway construction, or

5. Low quality aggregates are beneficiated and used.

Some of these possibilities such as transporting aggregate into the region, would probably increase the cost of aggregate while the effect of others, such as increasing aggregate production, might have little effect on cost or even reduce aggregate prices.

Economic Feasibility of Using Waste Glass as Aggregate

It is apparent from the above discussion, that the economic feasibility of using waste glass as aggregate will vary considerably in different localities throughout the United States. The optimum conditions for successful utilization of this approach to recycling glass would include high landfill costs and high aggregate costs in an area. Even with these conditions present, however, the cost of separating refuse and processing the glass would be a critical consideration. It is very unlikely that glass collected at recycling centers can be economically recycled as aggregate. If donors are paid for the glass bottles at rates as low as $10 per ton, it is obviously not practical to use this material as a replacement for aggregate costing at most $7.00 per ton. Even if the bottles and labor at the recycling center are donated, crushing is required and, due to the relatively small volumes of glass involved, unit crushing costs would be high. Thus, when waste glass is collected at recycling centers, recycling into new containers offers more promise for economical utilization of the glass than using it as aggregate.

For a materials recovery system such as the one proposed by the National Center for Resource Recovery, however, the prospects for economical utilization of the glass fraction as an aggregate are more promising. The estimated revenues for this system have been calculated by assuming that 63 percent of the recovered glass is color sorted and marketed at $12 per ton. However, if color sorting equipment is not used in the system, due either to the absence of a market for cullet in the area or an inability to sort the glass to the desired degree of purity, use of the glass as an aggregate is preferable to simply disposing of it in a landfill. Crushing and screening equipment are included in the plant facilities and thus gradation control would not require additional equipment. Although the glass would have a lower value when used as aggregate, this usage would make a contribution to product revenues rather than incurring an additional cost for disposal. The variations in estimated annual revenue for varying end uses of the glass from a resource recovery system are shown in Table 59 and the return on equity for each of these assumptions is given in Table 60. The figures given in these tables are based upon data contained in the report by the National Center for Resource Recovery.

The first column in Table 59 gives product revenues for a 500 ton per day plant assuming that the glass fraction is not marketable and must be disposed of in a sanitary landfill. In column 2, glass revenues and disposal and processing fees are calculated assuming that 40 percent of the glass input is color sorted and marketed at $12 per ton while 24 percent is too small for sorting and is sold as aggregate for $1 per ton. Column 3 gives glass revenues and disposal and processing fees assuming that 64 percent of the glass input is marketed as aggregate at $1 per ton. Return on equity for these options is given in Table 60 for a case where 40 percent of capital is borrowed. Return on equity is only 6.4 percent if all of the recovered glass is landfilled, but rises to 10.2 percent if the recovered glass is sold as aggregate for $1 per ton and 14.6 percent if 63 percent of the recovered glass is sold for cullet at $12 per ton and 37 percent is sold for aggregate at $1 per ton. The $1 per ton value for glass used as aggregate is quite conservative, based upon the previously stated aggregate prices throughout the United States. If a value of $3 per ton is assumed, the return on equity rises to 11.7 percent when all of the glass is used as aggregate. It should be noted again that these figures are based upon assumed disposal fee of $6.50 and processing fee of $2.00 per ton. Other assumptions concerning operating costs, equipment costs, and product revenues are detailed in the report by the National Center for Resource Recovery.

This analysis indicates that waste glass can be economically reclaimed from municipal refuse for use as aggregate only if the recovery system produces revenues from marketing additional components such as ferrous metals, aluminum, other non-ferrous metals, and paper and from disposal or processing fees. Disposal and processing fees are of particular importance since the value of recovered products does not cover the cost of extracting them from the refuse. This means that recycling of refuse components in general, and glass in particular, is not likely to be economical in a classical sense (not considering social costs) when costs for landfill disposal are low. In areas where conventional disposal costs are relatively high, and recycling offers an alternate means for treating solid wastes, the use of glass as aggregate can contribute revenues to the system even though the glass is not color sorted or the system is not conveniently located for transporting glass to a container manufacturer. The advantage of a local market for the glass as aggregate, especially in areas which have a deficiency in conventional aggregate supplies, may make this usage more attractive than shipping the glass some distance to a container manufacturer. Under conditions of high disposal costs and adequate market prices for other recoverable components, resource recovery systems may be able to obtain an adequate return on equity even though the glass aggregate brings in revenues of only $1 per ton. Higher aggregate prices will enhance the desira-

bility of using glass as aggregate under these same conditions but even at $7.00 per ton, revenue generated by the use of glass as aggregate would represent less than 10 percent of the total revenue necessary to insure a profitable operation of the resource recovery system.

TABLE 59

ASSUMED ANNUAL REVENUES FROM RESOURCE RECOVERY SYSTEM

Revenue Source	Conditions Outlined Below 1	2	3
Product Revenues			
Ferrous	$105,760	$105,760	$105,760
Aluminum	218,400	218,400	218,400
Glass	0	78,624	9,984
Fiber	62,400	62,400	62,400
Non-ferrous Materials	124,800	124,800	124,800
Total Product Revenues	$511,360	$589,984	$521,344
Disposal Fee	$120,458	$185,354	$185,354
Refuse Processing Fee	274,936	254,968	254,968
Total Revenues	$906,754	$1,030,306	$961,666

1. No optical sorting and no market for recovered glass. All glass landfilled.
2. Optical sorting. 63% of recovered glass selling at $12 per ton, 37% selling at $1 per ton.
3. No optical sorting. All recovered glass selling at $1 per ton.

Other assumptions:

a. 6.8% of input stream assumed to be recovered ferrous selling at $10 per ton.
b. 0.7% of input stream assumed to be recovered aluminum selling at $200 per ton.
c. 6.4% of input stream assumed to be recovered glass.
d. 4.0% of input assumed to be a mixture of hand picked newspaper, Kraft and corrugated selling at $10 per ton.
e. 0.4% of input assumed to be other non-ferrous metal selling at $200 per ton.
f. Assumes a fee of $6.50 per ton charge for every ton of refuse that does not have to be disposed of.
g. Assumes a $2 per ton refuse processing fee for shredding and air classifying the refuse.

TABLE 60

ASSUMED RETURN ON EQUITY FROM RESOURCE RECOVERY SYSTEM

	Conditions Outlined Below		
	1	2	3
Equity	$1,429,045	$1,445,513	$1,429,045
Debt	970,000	970,000	970,000
Capitalization	$2,399,045	$2,415,513	$2,399,045
Annual Revenue	$906,754	$1,030,306	$961,666
Annual Operating Cost	814,770	818,511	814,770
Profit	$ 91,984	$ 211,795	$146,896
Return on Equity	6.4%	14.6%	10.2%

1. No optical sorting and no market for recovered glass. All glass landfilled.
2. Optical sorting. 63% of recovered glass selling at $12 per ton, 37% selling at $1 per ton.
3. No optical sorting. All recovered glass selling at $1 per ton.

ACKNOWLEDGMENTS

The project is indebted to many individuals and private as well as public agencies throughout the nation for information and assistance in the conduct of the study. The list of those who have been particularly helpful includes the following:

John H. Abrahams, Jr., Glass Container Manufacturers Institute, Washington, D.C.

Harold A. Aschinger, Anchor Hocking Corporation, Winchester, Indiana

W. R. Bennett, Ontario Department of Highways

H. Elliot Dalton, Glass Container Council of Canada

Charles G. Depew, Owens-Illinois, Inc., Toledo, Ohio

J. J. Kaller (Retired), Municipality of Burnaby, Burnaby, British Columbia

Henry Kayser (Retired), Industrial Asphalt, Van Nuys, California

Milton F. Masters, Industrial Asphalt, Van Nuys, California

De L. Miller, Brockway Glass Co., Brockway, Pennsylvania

Pickett Scott, Glass Containers Corporation, Fullerton, California

Thomas A. Smith, Omaha Testing Laboratories, Inc., Omaha, Nebraska

and officials of the California, Pennsylvania, Ontario, and British Columbia Departments of Highways.

Graduate research assistants who participated in the study included Charles Foster, Michael Korth, John Doyle, Thomas Keith, Ching-Tzu Lu and Dwarka Gupta.

REFERENCES

1. Golueke, C.G. Recycling and reusing resource residues. Compost Science 12(3): 4-8, May-June 1971.

2. Vaughan, R.D. Reuse of solid wastes: A major solution to a major national problem. Waste Age 1(1): 10-15, Apr. 1970.

3. Hickman, H.L. Characteristics of municipal solid wastes. Scrap Age 26(2) 305-307, Feb. 1969.

4. Bell, M. Characteristics of municipal refuse. In National Conference on Solid Waste Research, Chicago, 1963. American Public Works Association. p. 28-38.

5. Kaiser, E.R. Chemical analyses of refuse components. Paper 65-WA/PID-9. In Proceedings, American Society Mechanical Engineers, Nov. 7-11, 1965. 5p.

6. Resource recovery from incinerator residue. Vol. 1 Findings and conclusions. A report for the Bureau of Mines, U.S. Department of the Interior prepared in cooperation with the Institute for Solid Wastes of the American Public Works Association [Chicago] Nov. 1969. p. 2.

7. Glass Containers, sub-council report. National Industrial Pollution Control Council [Washington D.C.] Feb. 1971. 21 p.

8. Golueke, C.G. and P.H. McGauhey. Comprehensive studies of solid waste management. Public Health Service Publication No. 2039, Washington, U.S. Government Printing Office, 1970. p. 111-112.

9. Malisch, W.R., T.E. Keith, D.E. Day, and B.G. Wixson. Effect of contaminants in recycled glass utilized for glasphalt. In Proceedings; Third Mineral Waste Utilization Symposium, Chicago, Mar. 14-16, 1972. U.S. Bureau of Mines and IIT Research Institute. p. 371-384.

10. Goode, J.F., and L.A. Lufsey. A new graphical chart for evaluating aggregate gradations. In Proceedings; Association of Asphalt Paving Technologists, New Orleans, Jan. 29-31, 1962. p. 176-207.

11. Miller-Warden Associates. Effects of different methods of stockpiling and handling aggregates. National Cooperative Highway Research Program Report 46. Highway Research Board. 1967. p. 7.

12. Goode, J.F., and E.P. Owings. A laboratory-field study of hot asphaltic concrete wearing course mixtures. American Society for Testing and Materials Special Technical Publication 309. 1962. p. 1-21.

13. Road Research Laboratory. Bituminous Materials in road construction. London, Her Majesty's Stationery Office, 1962. p. 82.

14. Lefebvre, J. Recent investigations of design of asphalt paving mixtures. In Proceedings; Association of Asphalt Paving Technologists, Atlanta, Feb. 25-27, 1957. p. 321-361.

15. Introduction to Asphalt, 6th ed. Manual Series No. 5. The Asphalt Institute. College Park, Md. Apr. 1970. p. 66.

16. Bennett, W.R. Crushed-glass in asphalt pavement construction: a feasibility study. D.H.O. Report No. IR41, Department of Highways, Ontario, May 1971. 12 p.

17. Kummer, H.W., and D.F. Moore. Concept and use of the British portable skid resistance tester. Joint Road Friction Program: Pennsylvania Department of Highways and the Pennsylvania State University, Report No. 6, June 1963. 27 p.

18. Kummer, H.W. and W.E. Meyer. Tentative skid-resistance requirements for main rural highways. National Cooperative Highway Research Program Report 37. Highway Research Board. 1967. 80 p.

19. Gallaway, B.M., and G.R. Vavra. The effect of silicone on the raveling characteristics of hot mix asphalt paving mixtures. In Proceedings; Association of Asphalt Paving Technologists, Atlanta, Feb. 26-28, 1968. p. 422-433.

20. Personal communication. A.G. Veith, The B.F. Goodrich Company, to W.R. Malisch University of Missouri-Rolla, Jan. 22, 1971.

21. Rose, J.G., and J.H. Havens. Aggregate shape and skid resistance. Kentucky Department of Highways Research Report KYHPR-71-66; HPR-1(7), part II. Sept. 1971.

22. Lowne, R.W. The effect of road surface texture on tyre wear. Wear 14(1): 57-70, 1970.

23. Cannella, Albert A. The refuse disposal problem. Public Works 99(2) 116-120, Feb. 1968,

24. Quimby, Thomas. Resource recovery. Waste Age 4(1) 24-28 Jan.-Feb. 1973.

25. DeMarco, Jack, D.J. Keller, J. Leckman and J.L. Newton. Incinerator Guidelines 1969. Public Health Service Publication No. 2012, Washington, U.S. Government Printing Office, 1969. p. 8-10.

26. Bargman, Robert D. Urgent need to recycle wastes? Civil Engineering 42(9) 107-109, Sept. 1972.

27. Stanczyk, M.H., and J.A. Ruppert. Continuous physical beneficiation of metals and minerals contained in municipal incinerator residues. In Proceedings; Second Mineral Waste Utilization Symposium, Chicago, Mar. 18-19, 1970. U.S. Bureau of Mines and IIT Research Institute. p. 255-262.

28. Herbert, W. Solid waste recycling at Franklin, Ohio. In Proceedings; Third Mineral Waste Utilization Symposium, Chicago, Mar. 14-16, 1972. U.S. Bureau of Mines and IIT Research Institute. p. 305-310.

29. Solid Waste Report 2(1) 4, Jan. 11, 1971.

30. Sullivan, P.M. and M.H. Stanczyk. Economics of recycling metals and minerals from urban refuse. Bureau of Mines Solid Waste Research Program Technical Progress Report-33, Apr. 1971, 19p.

31. Materials Recovery System Engineering Feasibility Study. National Center for Resource Recovery, Inc. Washington D.C., Dec. 1972.

32. Engineering News-Record 190(1) 30-31, Jan. 4, 1973.

33. Marek, Charles R., M. Herrin, C. Kesler and E. Barenberg. Promising replacements for conventional aggregates for highway use. National Cooperative Highway Research Program Report No. 135. Highway Research Board. 1972.

LIST OF PUBLICATIONS

Malisch, W.R., D.E. Day and B.G. Wixson. Use of domestic waste glass as aggregate in bituminous concrete. Highway Research Record (307): 1-10, 1966.

Malisch, W.R., D.E. Day and B.G. Wixson. Use of waste glass for urban paving. In Proceedings; Second Mineral Waste Utilization Symposium, Chicago, Mar. 18-19, 1970. U.S. Bureau of Mines and IIT Research Institute. p. 369-373.

Malisch, W.R., D.E. Day, and B.G. Wixson. Streets of glass. The American City 85(7): 104, 106, July 1970.

Day, D.E., W.R. Malisch, and B.G. Wixson. Improved bonding of waste glass aggregate with bituminous binders. Ceramic Bulletin, 49(12): 1038-1041, Dec. 1970.

Malisch, W.R., D.E. Day, and B.G. Wixson. Use of salvaged waste glass in bituminous paving. In Proceedings; Technology for the Future to Control Industrial and Urban Wastes, Rolla, Mo., Feb. 8-9, 1971. University of Missouri - Rolla. p. 26-31.

Malisch, W.R., D.E. Day and B.G. Wixson. Reusing scrap glass. In Proceedings; Design of Consumer Containers for Re-Use or Disposal, Columbus, Ohio, May 12-13, 1971. Battelle Memorial Institute and U.S. Environmental Protection Agency. p. 185-209.

Malisch, W.R., D.E. Day, and B.G. Wixson. Utilization of waste glass in asphaltic pavements. In Proceedings; Fourth Buhl International Conference on Materials, Pittsburgh, Nov. 16-18, 1971. Carnegie-Mellon University. p. 444-453.

Wixson, B.G., W.R. Malisch, D.E. Day, and J.H. Abrahams. Methods for recycling glass from industrial and municipal solid wastes. In Proceedings; 27th Annual Purdue Industrial Waste Conference Lajayette, Ind., May 2-3, 1972. Purdue University (In press).

Malisch, W.R., B.G. Wixson, and D.E. Day. Asphalt paving using glass aggregates: current status of knowledge. In Proceedings; III Inter-American Conference on Materials Technology, Rio de Janeiro, Brazil, Aug. 14-17, 1972. (In press).